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RADC-TR-76-142
Final Technical Report
May 1976

ELECTRO-OPTICAL RECTIFIER (EOR) UPDATE STUDY

Bendix Research Laboratories

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

This report has been reviewed and approved for publication.

APPROVED: James R. Tremlett

JAMES R. TREMLETT
Project Engineer

APPROVED: Howard Davis

HOWARD DAVIS
Technical Director
Intelligence & Reconnaissance Division

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A study has been performed to determine means of improving the Electro-Optical Rectifier (EOR), which is an optical projection instrument for rectifying oblique frame, strip, and panoramic photography. The study consisted of an engineering analysis of the prestnt system, study and evaluation of alternate system designs, and development of a preliminary design for an improved EOR system. Preliminary design features include use of a dedicated digital computer to perform both the rectification calculations and system control functions in real time, a disk operating system, a digital servo system, new carriage

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drive gear boxes, high-performance motor/techometers, and a new servo drive that permits computer control of drum velocity.

SUMMARY

The Electro-Optical Rectifier (EOR) is a slit-scan optical-projection rectifier capable of rectifying oblique frame, strip, and panoramic photography. Image transformations are accomplished by programmed motion of the lens carriage, copy platen, and copy carriage. While the EOR has been a useful instrument, its present control system has become obsolete.

The EOR Update Study covered an engineering analysis of the present system, study and evaluation of alternate system designs, and development of a preliminary design for an improved EOR system. In the initial phase of the study, an engineering analysis was performed on an EOR system at the Defense Mapping Agency Aerospace Center (DMAAC), St. Louis, Mo. Tests were performed to determine system capabilities and limitations. Alternative techniques, components, and equipment were then investigated to determine their applicability to the EOR system, and comparative evaluations were made to select the most promising combination of improvements. Based on this effort, a preliminary design was developed for an improved EOR system.

In the preliminary design, a dedicated digital computer would perform both the rectification calculations and system control functions in real time. This independent controller system would provide more reliability and flexibility than the present numerically controlled rectifier system. To facilitate initial program development and future program expansion, a disk operating system is recommended. Other design features include replacement of the present analog servo electronics with a digital servo system, replacement of gear boxes in the carriage drive systems to reduce backlash, replacement of carriage and platen motors and tachometers with modern high-performance motor/tachometers, and replacement of the present drum drive system with a servo drive system that allows computer control of drum velocity.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EVALUATION

The Electro-Optical Rectifier (EOR) is presently the only production oriented rectifier within the DOD mapping and charting community with the capability to transform both color and black and white aerial imagery from virtually any camera system. The production efficiency of the system has been seriously impaired due to frequent component malfunctions. It has become increasingly apparent over the past several years that the only approach available for continuing the functional life of this vital piece of production hardware would be to update the system. Therefore, the subject effort was undertaken to determine where modifications could be implemented to provide a highly reliable system capable of functioning in a production environment. The engineering analysis identified the deficiencies within the hardware which if corrected would significantly improve system reliability and maintainability. These deficiencies and proposed modifications for alleviating them are documented in this final report.

The final report is an integral part of the follow-on effort which will provide for the upgrade of all EOR systems. The upgrade will remedy the system's deficiencies allowing the EOR's to continue in a very useful production role.

James R Tremlett
JAMES R. TREMLETT
Project Engineer

SECTION I

INTRODUCTION AND SUMMARY

This report documents work performed on the Electro-Optical Rectifier (EOR) Update study. The purpose of the study was to determine modifications which could be made to present EOR systems to improve their flexibility, reliability, and maintainability; and thereby increase their functional life. Study work included experimental tests to determine certain parameters of the present EOR units, analysis to determine the feasibility of various approaches to system improvement, and preliminary design work on recommended improvements. A preliminary design for an improved EOR system was established. The design is based on a digital control computer and digital servo systems.

1.1 INTRODUCTION

The Electro-Optical Rectifier (EOR) is a slit-scan, optical-projection rectifier capable of rectifying a broad range of photographic materials. Its theory of operation is based on optically transferring imagery lying along lines of constant scale in an input photograph to an output film. Rectification is accomplished by illuminating a line across the input photograph and imaging this line onto an output film,using a single lens. The input photograph is mounted on a stage which scans the photograph across the illuminated line in a direction normal to the line. As the input photograph is scanned, the output film is advanced by the motion of a rotating drum. A two-dimensional image is thereby transferred from the input photograph to the output film. During this process, magnification along the line (optical magnification) is varied by changing the positions of the lens and photograph with respect to the output film. Magnification normal to the line (in the direction of scanning motion) is varied by changing the scanning velocity of the input photograph with respect to the fixed velocity of the output film.

Although this EOR concept has been very successful, the present EOR control system has become obsolete. EOR systems have exhibited sensitivity to adjustment, and poor reliability and maintainability. Errors and physical imperfections in paper tape, which is generated by a separate computer system to drive the EOR, have also limited the effectiveness of the system. The EOR improvement study documented in this report was undertaken to determine solutions to these and other problems, and to develop a preliminary design for an improved EOR system.

1.2 STUDY APPROACH

It was determined at the beginning of the program that the improved EOR system should incorporate digital servo systems and a digital control computer to achieve the basic objectives of the retrofit program. The study effort was, therefore, directed toward examining alternatives and determining design parameters within this framework rather than considering a large set of different alternatives. In the study, two basically different approaches to digital computer control of the EOR system were investigated. The first approach is based on having the EOR system completely independent from other systems. With this approach, the control computer does the rectification calculations in addition to controlling the hardware during rectification. The second approach is based on performing the rectification calculations on the 1108 computing system as is presently done, and driving the EOR with the 1108 output magnetic tape. Since a preference for the independent system approach was indicated by DMAAC representatives early in the program, most of the design study effort concentrated on this approach.

A major component in the improved EOR system is the control computer programs. These programs must function in real time to control the operation of the EOR. A significant part of the study effort was, therefore, devoted to the definition of a program structure and various program modules of the improved EOR system. Since the rectification programs must be written in FORTRAN, a benchmark rectification program was coded and tested on a Digital Equipment Corporation (DEC) 11/35 computer. This experimental activity established the feasibility of certain approaches to program structure with respect to real time operation.

Several different computers were considered for the EOR task. The alternatives were compared on the basis of cost and ease of interfacing. A study was performed to determine how to interface the various computers to servo logic and parallel input/output hardware which has already been developed by Bendix. The study included definition of the various control signals required to drive the EOR hardware with the computer.

A servo design study was performed to determine servo control requirements of the EOR and to establish preliminary servo designs. Tests were performed on the present EOR systems to determine certain key characteristics of the present EOR servos and to determine torques required to operate the various mechanical drive systems of the EOR. Analysis was performed to determine specifications required for new servo systems, and specific servo components were identified (manufacturer and model number) for the servo systems.

A survey of presently available process lenses was conducted to find off-the-shelf replacement lenses which would increase light through the EOR optics. The possibility of using a single lens to cover the magnification range of 0.6X to 6X was also examined. The light source and condenser optics were studied with the objectives of increasing light and/or achieving a better color reproduction capability.

As part of the overall system design study, various mathematical analyses were performed. These included analyzing effects of slit width and carriage position errors on resolution, and determining relationships between carriage position errors and output geometric errors of the EOR.

1.3 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The recommended approach to digital computer control of the EOR system is to have the computer perform both the rectification calculations and the system control functions in real time. This independent controller system approach provides the most reliability and flexibility. For compatability with readily available servo interface equipment it is recommended that the PDP 11/35 be selected for the control computer. To facilitate initial program development and future program expansion, a disk operating system such as DEC DOS/BATCH is recommended.

It is recommended that the analog servo electronics be replaced with digital servo systems. Gear boxes in the copy and lens carriage drive systems should be replaced to reduce backlash. Carriage and platen motors and tachometers should be replaced with modern, integral motor/tachometer units for higher torque, improved dynamic accuracy, and longer life. It is also recommended that the present drum drive system be replaced with a servo drive system to allow computer control of drum velocity.

With some modification of the lens turret and copy carriage cable routing it is possible to use a single 10-3/4 inch focal length lens to cover the range of 0.6X to 6X optical magnification. A possible lens for this purpose is presently available from Rolyn Optics. Other lenses having larger apertures which might be used to replace the present lenses are also available. None of these lenses have been tested for resolution, so their use in the EOR would be experimental.

A higher power mercury lamp is available for increasing light in the EOR system, but its use is not recommended because of increased heat and the need for a new high voltage power supply. Use of xenon lamps in the EOR is also not recommended because of the large amount of infra-red energy they radiate. With a servo controlled print drum, better color reproduction can be obtained by using color correction filters on the present lamp and running the drum at a slower speed.

1.4 SUMMARY OF REPORT

Section 2 of the report documents the various project studies. Each subsection of Section 2 discusses specific study results, conclusions and recommendations. In Section 3 the various conclusions and recommendations of Section 2 are summarized. Appendix A presents a derivation of image motion smear transfer function, and Appendix B consists of benchmark program listings. Appendix C presents a description of the recommended system preliminary design.

SECTION 2

EOR STUDY

This section documents the various studies which were performed as parts of the overall EOR study. Section 2.1 discusses the system approaches which were considered during the study. Section 2.2 discusses various factors which affect the selection of the control computer and a suitable set of peripheral devices. Section 2.3 documents the computer programs study. Results of benchmark program runs of a frame rectification program are presented in this section. Section 2.4 documents a study which determined how to interface the EOR to the various control computers. The servo design study is documented in Section 2.5; this section includes results of the various tests performed on the servos of the present EOR system. Section 2.6 presents results of study effort on optical components of the EOR. This section discusses the possible use of a single lens to cover a magnification range of 0.6X to 6X. In Section 2.7 several mathematical analyses which were performed as part of the EOR study are presented. These include analyses of the effects of slit width and carriage position errors on resolution, and the relationships between carriage position errors and output print errors.

2.1 EOR SYSTEM CONTROL ALTERNATIVES

In the EOR system study, two basically different approaches to implementing computer control of the EOR were considered. The first approach, which is the preferred one, utilizes a computer control system which is completely independent of other systems. The second approach is conceptually similar to the present system where rectification computations are done off-line on the 1108 computer system and the EOR system is driven by a data tape. Because DMAAC personnel indicated a preference for the independent controller, study effort was concentrated on this approach. The following paragraphs discuss the two basic system alternatives and some of their variations.

2.1.1 Independent Controller System

The independent controller system approach results in an EOR rectifier system which is completely self-contained. It requires no external preprocessing of information prior to the rectification operation. Such a system might consist of a control computer with a disk operating system, a cartridge disk unit, a CRT terminal for entry and display of data, an operator control panel, and an interface through which the EOR is controlled. Programs within the control computer generate print drum velocity, and solve the requisite rectification relationships in real time to control the positions of the print drum, copy platen, copy carriage, and lens carriage. A set of rectification programs is available in the computer system to provide rectification of a variety of photograph types such as oblique frame, panoramic, and strip. The rectification programs are written in FORTRAN so that the user of the EOR system can easily modify or add to the set of rectification programs. Programs which actually control the EOR servos are written in assembly level language and are optimized for speed of execution. The functions of these programs, which include servo rate limiting, acceleration limiting, and servo position error compensation, are independent of the rectification geometry and need not be modified by the user. In addition to the rectification mode programs, the system includes programs for calibration and maintenance.

To operate the independent controller system, the operator enters rectification parameters through the CRT terminal. He then mounts and aligns the photograph on the copy platen, and loads the film drum. Depressing a START button then causes the system to generate a rectified print on the output drum according to the selected rectification program and the parameters entered for that program. When finished, the system stops and signals the operator.

The primary advantage of the independent controller system is that it is self-contained and does not rely on the availability of an off-line preprocessing computer for generation of servo commands. Since rectification computations are done in real-time during the printing operation, the production time associated with this step is eliminated. Elimination of the time lag between rectification calculation and printing also greatly reduces turn-around time for runs which must be repeated because of inadvertant use of wrong parameters or other such unpredictable events. Since no physical storage medium such as paper tape or magnetic tape is used to convey servo commands from the rectification calculations to the servo controller, repeat runs due to tape errors are eliminated.

In the independent controller system, rectification programs are written in FORTRAN and utilize FORTRAN library subroutines during execution. The control computer for this system must, therefore, have a software operating system and the necessary peripherals to support FORTRAN programs. Since part of the programs are written in assembly language, the system software must also allow for mixing (linking) FORTRAN and assembly language programs. Because the programs must control the EOR in real time, the control computer must be capable of executing instruction rapidly, implying the use of hardware rather than software for arithmetic functions such as multiply and divide, and possibly also for floating-point arithmetic. All of these necessary or desirable features require a more expensive control computer system than that which might be used with a simpler system.

With the independent controller system approach, certain variations in operating modes are possible. It is possible, for example, to perform a rectification run without actually printing. This is useful to determine whether or not EOR physical limits are exceeded without ruining a piece of film. The trial run can be made at a faster-than-normal speed with the servos disconnected (in software) so as not to waste time. It is also possible to perform the rectification calculations and control printing as two separate operations. The FORTRAN rectification programs can be run and the resulting servo commands stored on the disk. This program run need not be made in real-time. As a separate operation, the data on the disk can be played back to control the servos for printing. This approach has the advantage of not requiring fast computer hardware. If the system is equipped with a magnetic tape unit, it would be possible to configure the independent controller system as a tape driven system (described in the next section) which could use tapes generated by either itself or the 1108 system. Because of its many advantages, the independent controller system is recommended for the improved EOR system, and is described in more detail in Appendix C.

2.1.2 Tape-Driven Controller System

The tape-driven controller system is conceptually similar to the present EOR system. In this system, rectification computations to determine carriage commands are done on the 1108 using the present 1108 EOR programs. The magnetic tape output, however, is used directly to drive the EOR system, eliminating the paper tape conversion step of the present system. The tape-driven controller system could consist of a small control computer, a CRT terminal for data entry and display, an operator control panel, a magnetic tape unit to read the 1108 output drive tape, and an interface through which the EOR hardware is controlled. In such a system, the control computer reads position commands from the 1108 magnetic tape and drives the various servos accordingly. The computer programs interpolate between the coarsely recorded points from the drive tape to produce smooth servo motion. Other real time functions performed by the programs include servo velocity limiting, acceleration limiting, and position error compensation. In addition to the programs which control printing, there are programs for maintenance and calibration of the system.

To perform a rectification run on the tape-driven system, the operator mounts the 1108 drive tape on the magnetic tape unit, positions the photograph on the copy platen, and loads the film drum. Using the CRT terminal as a communication device, the operator then reads the first magnetic tape block and initializes the servo positions. Since the print drum is servo controlled, the operator can enter an arbitry print velocity. Depressing a START button on the control panel then causes the system to read position data from magnetic tape and drive the various servos accordingly. During the rectification run, servo positions can be displayed in real time on the CRT terminal.

The primary advantage of the tape controlled system is its lower cost. Since the computer is not required to run FORTRAN programs in real time, the computer hardware and operating system can be simple. The computer is programmed in assembly language for speed optimization. Additions to or modification of the rectification programs are done on the 1108 so the EOR control computer system does not have to be configured for ease of program modification.

While there are cost savings of the tape-driven system with respect to the independent controller system, these savings are not great. Hardware cost savings are not large. During the computer programs study, the mathematical model of the present EOR programs was reviewed. If a limited set of these programs such as linear enlargement, frame, panoramic, and strip were all that is required, the FORTRAN programming effort required would not be great. The fact that the tape-driven system would not require rewriting these FORTRAN programs is, therefore, not a great advantage.

2.1.3 Dual System Controller

With either the self-contained system or the tape-driven system, there is a possibility of using a single computer to control two EOR systems. In such a system, the control computer and its resources would be time-shared between two sets of programs. This possibility was not pursued in depth in the study, but certain observations can be made about this approach.

The computer programs for the dual system would be much more complex than for the single systems. Although system software is available from computer manufacturers for running multiple real time programs on a single computer, it is not clear that the programs could be run fast enough on a small computer to do an adequate job of servicing the servos. Experience with a similar system where a stereoplotter and printer were controlled simultaneously indicates that it is possible, but special programming was used. In the plotter/printer system, all programs were written entirely in assembly language (no FORTRAN), including a task scheduler. No operating system was used (except for certain I/O service routines), so operating system overhead was minimal. This system used a PDP 11/45 with floating-point processor.

In addition to the increased programming difficulty, the dual system controller concept has certain operational shortcomings. In the event that one of the EOR units required service, it would be cumbersome at best running diagnostics and other maintenance programs simultaneously with production on the other unit. One can, of course, provide separate CRT terminals, etc. for each unit, and structure the maintenance programs for dual operation also, but this increases the cost of the system. If the control computer malfunctions, of course, neither system can be used for production.

Evaluation of this approach is a matter of weighing its disadvantages against the cost savings obtained by only having to purchase one computer system. In the case of the independent controller system, the price of a computer, disk unit, and CRT terminal can be saved. In the case of the tape-driven system, the price of a computer and CRT terminal can be saved, but two magnetic tape units would still be required for simultaneous rectification operation.

2.2 CONTROL COMPUTER AND PERIPHERALS

Hardware and software must be chosen to optimize EOR systems for production. Speed, reliability, and ease of operation are necessary characteristics for the new EOR systems. The specific computer/peripheral-device-set/software combination that best achieves these characteristics is different for the various EOR system control alternatives mentioned in Section 2.1. In the following paragraphs the selected optimum combination for each alternative is discussed. Requirements of the first, developmental system are mentioned also.

2.2.1 Independent Controller System

The independent controller system approach requires a fairly sophisticated computer capable of handling a variety of tasks. It must be fast enough to solve the requisite rectification calculations for real time control of the print drum, copy platen, copy carriage, and lens carriage. Such speed requirements suggest that the computer should be equipped with hardware arithmetic functions. Software subroutines to accomplish assembly language multiplies, divides, and floating-point operations take time to design and code, and are much slower than corresponding hardware functions.

Rectifier outputs must be accurately spaced time-wise in order to provide efficient, smooth servo motion. Consequently, the computer must have a clock interrupt feature with outputs occurring at the start of each clock cycle. Custom-designed interfaces between the computer and the rectifier unit should be readily accommodated. Also, the computer should support a wide range of peripheral devices for both I/O and storage, and provide for adding a sufficient amount of easily accessed memory.

Software configuration requirements for the computer are threefold. First, there must be diagnostic programs capable of testing the equipment supplied by the computer's manufacturer. Second, there must be adequate system software available for developing application programs. A text editor, an assembler, a FORTRAN compiler, a linker, and a debugger are essential. The linker must be able to link overlay structures and FORTRAN programs with assembly language programs. Third, there must be a software operating system which runs in conjunction with application programs to support FORTRAN. If the operating system also provided interaction with all peripheral devices, it would save a great deal of effort in designing and coding the application programs. All of the computer's software should be able to be purchased on a suitable medium; i.e., the peripheral device required for loading system software into the computer should be able to be used for other purposes in the EOR system.

A search for those marketed computers most suitable for the independent controller system resulted in three possibilities. Judged to be interchangeable, the three computers are Digital Equipment Corporation's PDP-11/35, Modular Computer System's MODCOMP II/25, and Data General Corporation's Nova 2/10. Any one of the three would serve the purposes of the new EOR system well.

All three computer manufacturers offer disk operating systems for the computers selected. Disks are tremendous time-saving and, therefore, cost-saving devices. Upon execution of the application programs, time is saved because the basic program and subsequent overlays take only a few seconds to load from disk into memory. Loading programs from paper tape can be a lengthy task taking many minutes. If a random overlay structure is used with paper tape, the operator must be responsible for positioning the paper tape at the overlay to be read next. With a disk system the operator need not even be aware that an overlay structure exists.

During the development of application programs the time-saving feature of a disk is particularly evident. The disk serves as the storage medium for all system software required for program development as well as for the application programs themselves. A system software program, such as the editor, loads from disk into memory in seconds. Once the editor is resident in memory the programmer easily reads part of the application programs into memory, makes changes or additions to it, and stores the new version back on disk. Editing, assembling or compiling, and linking all are more rapidly performed. Because of the ease with which programs are modified, changes probably are made more often than if a paper tape or a magnetic tape medium were being used. With a paper tape system the tendency is to put program changes on short patch tapes in order to avoid punching the entire program. Keeping track of which changes are on which patch tapes is an arduous bookkeeping task. When many patch tapes accumulate or no more modifications need be made, the changes on the patch tapes are incorporated into the one long program tape. Sometimes a change is forgotten, causing redundant program debugging to occur. With both magnetic tape and paper tape systems, program bugs are often fixed temporarily by changing the erroneous words in memory after the program is loaded. These changes are made by way of the debugger or computer console and are in machine language. The machine language code is difficult to determine, and the determination in itself is error-prone.

Beyond saving time, a disk can also save memory space. Data required only at specific points during the execution of the application programs can be stored in files on disk and read into memory only as needed. Additionally, the disk can provide for intermediate storage of unique data produced during the program run.

A removable cartridge disk is judged to be a necessary peripheral device for the independent controller system. Other devices deemed necessary are a CRT terminal, a teletype, and one magnetic tape unit. A terminal is required to provide for communication between the operator of the EOR system and the programs. The operator enters parameters and directives by way of the terminal, and the program prints informative messages to the operator by way of the terminal. In the independent controller system such required communication is profuse. Consequently, the most suitable terminal for the system is a CRT terminal because it has the advantage of being much faster on output than mechanical terminals. Messages that are longer and more complete can be printed by the program with no waste of time. Also, a continuous dynamic display of changing data is feasible only on a CRT terminal (with an addressable cursor). During development of the EOR programs the CRT would be used by the programmer to communicate with the computer's system software. Because of its speed, the CRT terminal would save program development time.

A teletype or some other printer is truly necessary only for program development. The programmer must have some way of obtaining hardcopy listings of the EOR programs. Although a teletype is a required purchase for the first EOR system alone, it is easy to envision its usefulness on all production systems. For example, it could be used to produce a hardcopy of information resulting from a rectification run or calibration run. Furthermore, its paper tape feature could provide for entering parameters by way of paper tape as an alternative to the operator typing them into the computer by way of the CRT terminal.

Backup copies of the disk should be made periodically as insurance against the destruction of disk contents. The frequency with which copies are made depends on how often changes are made to disk contents. On the EOR system, for example, a disk save should be performed whenever the carriages are recalibrated, since a new set of calibration data then exists in a file on the disk. Magnetic tape is a good medium on which to save disk contents. If the EOR production systems are in close proximity to one another, only one need have a magnetic tape unit attached to it. The disks for all of the EOR systems can be copied onto magnetic tape at that one system. The only incovenience, then, is a necessity to schedule disk-saving sessions.

Another use for magnetic tape stems from the fact that the computer's disk operating system software can be purchased on magnetic tape for transference onto the disk. Therefore, a nine-track, industry-standard magnetic tape unit should be part of the first, developmental EOR system.

2.2.2 Tape-Driven Controller System

The requirements of the tape-driven controller system call for a computer from the same class as the computer for the independent controller system with the difference that fewer hardware features need be purchased as part of the computer package. In other words, the three computers selected for the independent controller system are also appropriate for the tape-driven controller system, except possibly for the MODCOMP II/25, which could be changed to a I/25. Hardware arithmetic functions are not required because lengthy rectification calculations are not done in real time. The calculations that do occur, interpolations of buffered magnetic tape data, are simple and take place in the background program as opposed to the clock program. Therefore, time requirements are not stringent.

The computer still must have a clock feature to provide for interval interrupts. Rectifier outputs must be accurately spaced to yield smooth servo motion. Interfacing between the computer and the rectifier unit should be readily handled, and the computer should support several peripheral devices for I/O.

There are two software requirements for the computer. First, there must be diagnostic programs which test the equipment supplied by the computer's manufacturer. Second, there must be developmental system software consisting at least of an editor, an assembler, a loader, and a debugger. There is no need for a FORTRAN compiler or an operating system. The routines written in FORTRAN in the independent controller system are the routines that perform the rectification calculations. These routines do not appear in the tape-driven controller system. Largely because of no necessity for FORTRAN or an operating system, less memory is required by the tape-driven system.

For the same reasons mentioned in Section 2.2.1, a disk would appear desirable as a peripheral device for the tape-driven system. However, it is not necessary. Operating time lost by loading programs into memory from paper tape can be made up in other ways. For example, setup time on the tape-driven system should be shorter than on the independent controller system due to the need for less operator-program communication.

Without a disk, a high speed paper tape reader/punch is a necessity to be used during application program development and for loading the EOR programs into the production systems. (This assumes that the computer manufacturer's software package is available on paper tape and not on magnetic tape.) Additionally, servo correction data resulting from calibration of the EOR unit's carriages would be punched on tape during calibration mode. The resulting tape would subsequently need to be read whenever the rectification program tape is read into memory.

A magnetic tape unit is an obvious peripheral device requirement for the tape-driven controller system since the magnetic tape output of the 1108 needs to be read if it is to be used to drive the EOR system. The only remaining devices needed are a CRT terminal and a teletype. There is not a great deal of operator-program communication, so a teletype would be an adequate terminal for the tape-driven system except for one drawback. A CRT terminal with an addressable cursor is necessary if a continuous dynamic display of changing data is desired. Assuming then that a CRT terminal is used for communication between the operator and the programs, the teletype is needed only for program development as in the case of the independent controller system.

2.2.3 Dual System Controller

There are two hardware configurations possible for the dual system controller. Which configuration is used depends on the desired method for operating the two EOR units. If one operator is to direct the functioning of both units, hardware would consist of a computer, a disk, one CRT terminal, one magnetic tape unit (or two if the dual system is to be tape driven), and a teletype. Under this configuration the two EOR units do not function completely independently. Any operator-program communication required during rectification setup, calibration operations, and diagnostic procedures must be directed toward one unit or the other. The only simultaneous functioning able to be envisioned is the operator communicating with the program concerning one unit while the other unit is busy rectifying. If the two EOR units are to operate completely simultaneously and independently, another CRT terminal for a second operator must be added to the above hardware configuration.

Regardless of the precise configuration, the computer in both cases must be one that is comparable to Digital Equipment Corporation's PDP-11/45 in speed and available features. Particularly if the dual system is not tape-driven, a hardware floating-point processor is required to make the computer fast enough to handle two sets of rectification calculations in one clock cycle. Because of program complexity memory should be expandable to 64K and the computer should be equipped with programmable priority interrupts. Considering aesthetics alone, priority interrupts and computer speed keep the operators in a two-person configuration from noticing lags in the operation of their individual CRT terminals. At a deeper level, these two features are required for simultaneous functioning of the EOR units. A disk with complete disk operating software is considered essential for the dual system controller.

2.3 COMPUTER PROGRAMS STUDY

The computer programs study was undertaken to determine the best design for the new EOR system programs. The study concentrated on the preferred independent controller system approach; consequently, this section discusses the study effort with respect to that approach. Because the recommended new system is completely self-contained, the study was unencumbered by concern for compatibility with other systems. The only restrictive considerations involved the new system's computer. The programs had to be designed for available hardware and software, and the cost of such hardware and software could not be prohibitive. The configuration outlined in Section 2.2.1 was assumed.

Program design depends to a large extent on intended methods for operating a system. The first step in the study, therefore, was to define desirable operating characteristics for the new EOR system. Specifically, a choice had to be made between operating flexibility and strict computer control.

In a system operated under strict computer control the program leads the operator step-by-step through all functions that must be performed. At each step the program asks the operator to make a yes/no decision, requests data entry, or tells the operator to perform some operation. The operator's response is checked by the program to see if it is appropriate. Consequently, the system is closely guarded against operator error. Furthermore, the operator can be relatively untrained and still operate the system. The major disadvantage of strict computer control is its rigidity. The operator cannot deviate at all from the operating path provided by the programs. Exceptional conditions that may require a slightly different procedure cannot be handled without changing the program itself. Also, should the operator make a mistake that is undetectable by the program, he is unable to correct his mistake without starting the programs over again.

In a system designed for operating flexibility the operator tells the program what to do next. The program might list a menu of possible functions for the operator to perform, but the operator orders the functions himself. He also enters data whenever he pleases. The program, in general, does not question the operator's actions. Consequently, a system operated in this fashion may be more prone to error, especially in the hands of an untrained operator. An advantage of the flexibile system is, however, that operator mistakes are easily corrected without having to start operations over again.

For the new EOR system a choice was made in favor of the flexible approach. Operation of the EOR system is not complex. Only a limited number of functions needs to be performed for each rectification. Once the operator is familiar with the system he should make very few mistakes. In short, the advantages of the flexible approach were judged to be of greater importance than the advantages of a strictly controlled computer system.

As soon as the flexible approach was selected, it became clear that the program handling the CRT terminal's I/O would be of central importance in the new EOR system. The operator can type entries to the program at any time and the program must always be ready to receive them. One way to make sure that no typed inputs are missed is to operate the CRT terminal in an interrupt-driven mode. However, it is not necessary to use CRT interrupts if the program has little computing to do and few peripheral devices are being used. Without interrupts the program must loop continually looking for CRT terminal inputs. The critical factors in determining whether or not to use interrupts are (1) what the program is doing besides CRT I/O and (2) how much time is required by the routines servicing CRT I/O. In the case of the new EOR system the only operations occurring in addition to the servicing of CRT I/O are the handling of the disk peripheral device and the performance of real time calculations in response to regular interrupts. Both disk handling and real time clock calculations are more important program functions than CRT I/O servicing. Therefore, if CRT interrupts were to be used they would have to be at a lower priority level than the disk and clock interrupts. Furthermore, although it is difficult to judge the time requirements of the CRT I/O servicing routines, it is expected that these servicing routines are not especially time-consuming. As a consequence it was decided to design the programs assuming that the CRT terminal is not operated in an interrupt-driven mode. Because of this assumption the CRT handler must be the core of the background program in the sense that it must be executed repeatedly and often.

Beyond being a function of operating procedures, program design also depends on the probability that the programs will need to be changed or expanded at a later date. If expectations are high that changes and additions are likely, it is best to do the following three things:

(1) Separate the programs into program sections or modules. Then when changes are made only the changed modules, not all of the programs, need to be assembled or compiled and linked to the other program sections.

(2) Develop an overlay structure. There is then less chance of running out of room in core memory when changes and additions are made.

(3) Write the programs in a high level language such as FORTRAN. Programs written in high level languages are more easily understood and changed.

For the new EOR system, future changes and additions are most likely for those program sections in which the actual rectification calculations take place. Several rectification options (frame, panoramic, linear enlargement, etc.) are desired currently, and new options probably will be added at a later date. Consequently, it was decided that the programs required by each rectification option should comprise one program module. Furthermore, especially since only one option can be used at a time on the rectifier, the rectification programs should be stored on disk in mutually exclusive overlays where one overlay exists for each option. The rectification calculations for each option fall naturally into two divisions: those performed once to initialize rectification variables and those executed repeatedly to generate positioning information throughout the rectification process. It was decided that each set of calculations should be written in FORTRAN in a well-defined format and stored as a subroutine. The first subroutine is called the initialize routine and the second is called the update routine.

The next step in the study was to resolve a problem concerning the update routine. Each pass through the routine results in new copy platen, lens carriage, and copy carriage positions for the next scan. The clock program then has the responsibility of using the computed values to position the servos. The update routine is time-critical because position information must be available for the clock program when the clock program is ready for it. Otherwise, the servos will not run smoothly and at maximum speeds. Therefore, a method of running the update routine on a regular basis had to be found.

Two methods of ensuring a regularly executed update routine were considered. The first method is depicted in Figure 2-1. The routine is performed at a priority level below the clock program but above the background program. Execution of the update routine is triggered by the clock program at the end of every nth clock cycle. Platen and carriage positions computed by the routine are metered out to the servos by the clock program over n clock cycles. The primary advantage of this method is that the execution time of the update routine is not limited severely. Its only time restrictions are the following:

(1) The update routine must complete its calculations within n clock cycles while the clock program is metering out the update routine's last previous results.

(2) There must be enough time left over during the n clock cycles and n must be small enough to allow frequent execution of the background program.

Two disadvantages of this method relate to program complexity. They are:

(1) The metering out of positional changes to the servos is an extra task for the clock program to perform. If a different update rate (n) is allowed for each rectification option, the task becomes more complicated.

(2) The manner in which the clock program triggers the update routine requires either extra hardware or additional software. The extra hardware approach involves an interrupt able to be set by the clock program to go off as soon as the clock cycle has completed. The interrupt starts the update routine. The

additional software approach requires the clock program to jump directly to the lower priority update routine at the end of every nth clock cycle. Special bookkeeping is required to ensure that the update routine returns to the clock-interrupted location in the background program when it is finished.

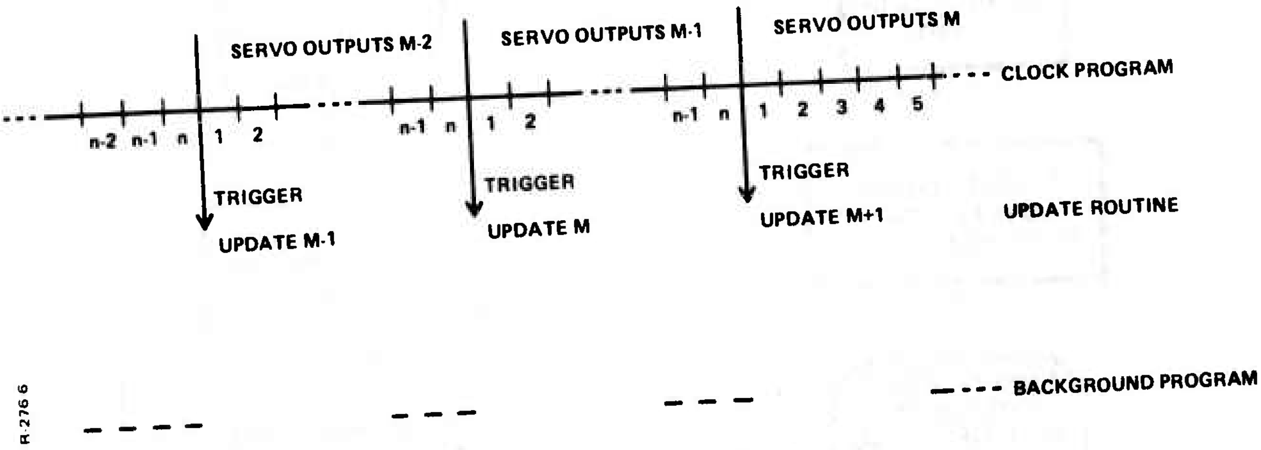

Figure 2-1 - Update Method I

The second method considered for executing the update routine is to call the subroutine as part of the clock program itself. Assuming the clock must cycle at 100 times per second for optimum servo operation, the routine is called every clock cycle or at some slower rate such as every other clock cycle. The rate depends on the amount of time needed by the background program. Regardless of the computation rate, the update routine must fit time-wise into one 10-ms clock cycle. To determine whether or not update routines can be completed within this time restriction on equipment under consideration, benchmark tests were performed on a PDP 11/35 computer. The tests were run twice. The first time they were run using the computer's floating-point option. The second time only an extended instruction set that includes hardware multiply and divide was used. Each test was written in FORTRAN to time-repetitive frame calculations under a different condition. The frame calculations were chosen because they seem to be the most demanding of all the rectification options, especially when the position of the rectified image (Vk) is less than or equal to zero. Under that situation the most FORTRAN library functions are called, and FORTRAN functions are time-consuming. Each test follows the format depicted in the flowchart of Figure 2-2. The calculations that "compute initial values for quantities needed later" are a subset of those that take place in the frame initialize routine. When a FORTRAN PAUSE statement occurs on the PDP 11/35, an action message is printed on the teletype. Typing CO continues the program. By continuing the program after the first PAUSE and keeping track of elapsed time until the second PAUSE it can be determined how long it takes for 10,000 iterations of the frame calculations to occur. Division of elapsed time by 10,000 yields the time it

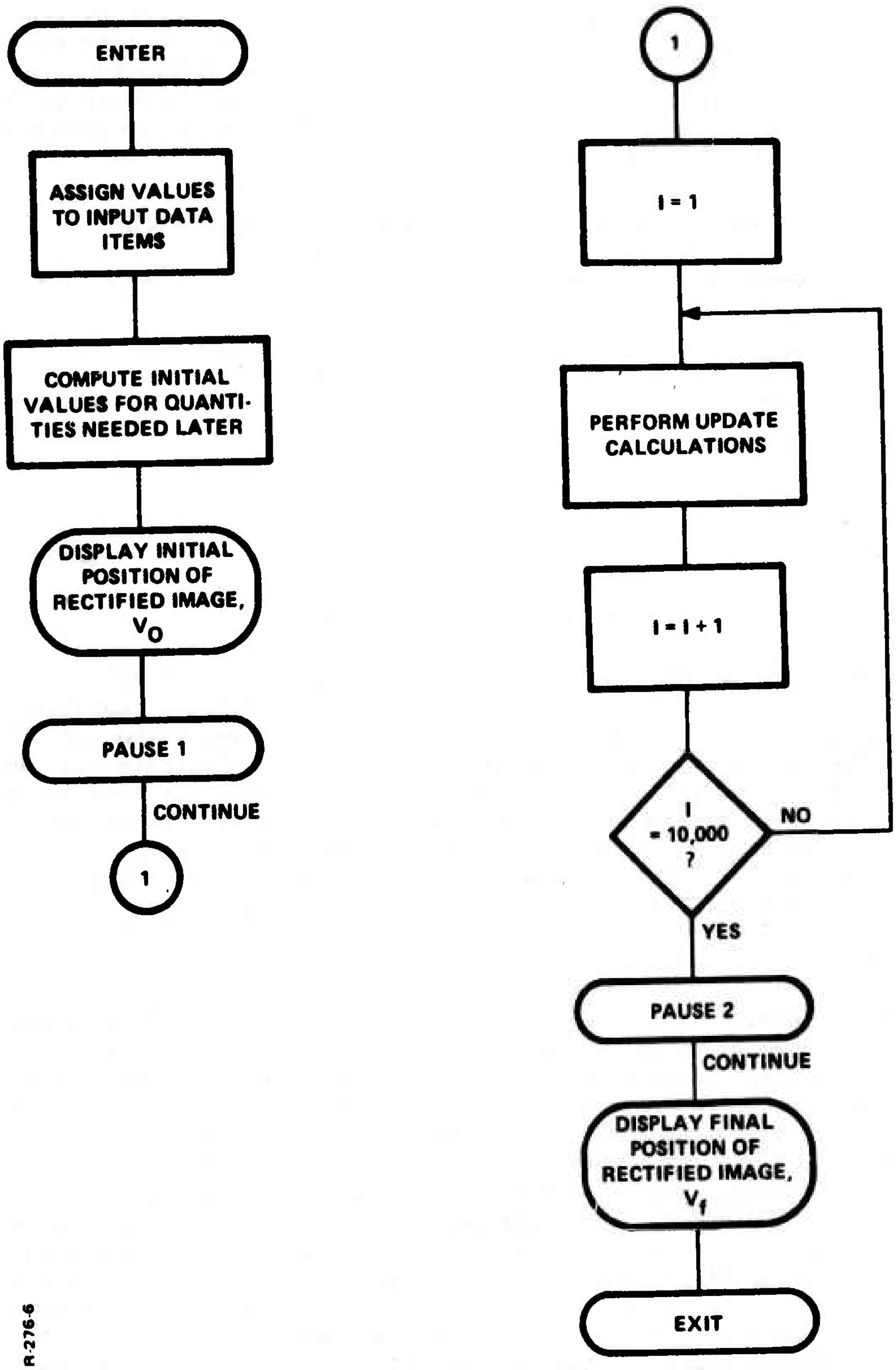

Figure 2-2 Flowchart of Benchmark Tests

takes for one iteration to occur. The initial position of the rectified image is printed before the first PAUSE and the final position of the rectified image is printed after the second PAUSE as a check on the test program. All of the test programs set the drum velocity input data item to a value of 0.0005 in./scan. Therefore, in 10,000 iterations the expected positional change of the rectified image is 5 in. The listings of the tests and the printouts resulting from running them are contained in Appendix B. The input data items used and the results of the tests are summarized in Table 2-1. Things to note about the tests are:

(1) Test 2, in which the Vk position of the rectified image is almost exclusively less than or equal to zero, took the longest time to execute.

(2) Although the data for test 1 is more complex than the data for test 4, they took about the same amount of time to run. In both of these tests the position of the rectified image is generally positive.

(3) The time for test 5, in which the position of the rectified image is positive half of the time and negative half of the time, is the expected result. That is, test 5 ran in a time that is half way between the results of test 2 and the results of test 4.

(4) The tests took over three times longer to run when only the extended instruction set was used instead of the floating-point option.

The conclusion resulting from the benchmark tests is that it is possible to run an update routine as part of the clock program provided that the computer used is as fast as a PDP 11/35 equipped with the floating-point option. In view of the fact that it is easier to implement, this method is the preferred method for executing update routines. The first method discussed can serve as a backup alternative in the event that timing becomes radically different than expected from the benchmark tests or a slower computer is used.

An unexpected conclusion reached from the tests concerns current EOR analytics. In developing the benchmark tests it was originally planned to use a negative value or zero as the initial position of the copy (input data item vo) in test 2. Attempts made to run test 2 under those conditions caused initial calculations to be indeterminate. A small positive number was finally assigned to vo for test 2. Benchmark test 3 was then written to determine why the original strategy caused errors. (Test 3 results are not shown in Table 2.) The input data items for test 3 were made identical to those for test 2 except for vo which was set to -1.0. Various intermediate values within the initial computations were printed out. From them it was found that the relationships

Table 2-1 - Summary of Benchmark Tests

		Test 1	Test 2	Test 4	Test 5
Input Data Items*	vo	1.37"	0.1"	4.9"	2.5"
	S	1.0	1.0	1.0	1.0
	t	45.0°	0°	0°	0°
	h	100.0 naut.mi.	1.0 naut.mi.	1.0 naut.mi.	1.0 naut.mi.
	f	6.0"	6.0"	6.0"	6.0"
	R	3439.0 naut.mi.	3439.0 naut.mi.	3439.0 naut.mi.	3439.0 naut.mi.
	ΔV	0.0005"/scan	0.0005"/scan	0.0005"/scan	0.0005"/scan
	F	13.9763779"	13.9763779"	13.9763779"	13.9763779"
	N	0.0984252"	0.0984252"	0.0984252"	0.0984252"
Results*	Vo	9.9"	0.1"	4.9"	2.5
	Vf	4.9"	-4.9"	-0.1"	-2.5
	1. With Floating Point	3.6 ms/iteration	6.0 ms/iteration	3.6 ms/iteration	4.8 ms/iteration
	2. Without Floating Point	11.8 ms/iteration	19.7 ms/iteration	11.1 ms/iteration	15.4 ms/iteration

* Notation is the same as that used in present EOR documentation.

used in the initial calculations are true only when α, the tilt of vo, is positive. The conclusion is that current EOR analytics should be examined closely for further restrictions like the one for vo. Changing the analytics to remove such restrictions will result in expanded operational capabilities under the new programs.

The computer programs study resulted in the design discussed in Appendix C. The design incorporates characteristics mentioned in this section. Specifically, it allows for a great deal of operating flexibility, the programs are divided into distinct modules that fit into an overlay structure, FORTRAN is used for the rectification calculations, repetitive update computations are performed within the clock program, and the CRT terminal is operated without using interrupts. Before the rectification calculations are actually coded, current EOR analytics should be examined and optimized.

Should a tape-driven controller system be selected instead of the independent controller system, operating flexibility would still be a desirable design characteristic and CRT terminal I/O would still be processed as indicated in this section. Because of the lack of a disk, overlays would be more cumbersome. However, as in the design for the independent system, there probably would be three overlays, one each for rectification, calibration, and diagnostic functions. The discussion in this section concerning FORTRAN is not applicable to the tape-driven system since no rectification calculations are required.

2.4 INTERFACE STUDY

The objective of the interface study was to determine the amount and type of hardware required to interface the control computer to the EOR. To accomplish this, the various data and control signals which would be required for communication between the control computer and the EOR hardware were itemized. The number of signals, their widths (in bits), and their direction of signal flow (in or out of the computer) established the number of 16-bit input and output channels required for interfacing.

For the study, it was assumed that servo logic cards, parallel input cards, and parallel output cards, which have already been developed by Bendix Research Laboratories, would be used in the system. These cards connect directly to the UNIBUS of the DEC PDP-11 series computers, and are described in Appendix C. Because these cards are directly compatible with the DEC computer, selection of the DEC PDP-11/35 as the control computer will minimize interfacing cost. If the Modcomp or Nova computer is selected, a small additional amount interfacing hardware will be required.

2.4.1 EOR Interface Requirements

Assuming the print drum of the improved EOR system would be servo-controlled, there would be a total of four servo output channels required. These channels would convey digital incremental servo position commands from the control computer to the servo logic for the following servos:

(1) Print Drum

(2) Copy Platen

(3) Copy Carriage

(4) Lens Carriage

Each servo output channel would require 12 bits (11 bits plus sign) to take full advantage of the precision of the servo logic. A 16-bit output channel should be used for each servo channel, even though three channels would provide sufficient bit capacity. Servo outputs would therefore require four 16-bit output channels in the interface. In addition to the data bits, the interface equipment must also generate strobe pulses to transfer the data to the servo logic cards.

In addition to servo outputs, there are requirements for information transfer between the computer and the EOR hardware as single bits. These single-bit transfers provide control functions such as the shutter control and indicator lamps. They also provide sensing functions such as limit switch and zero pulse sensing. Table 2-2 lists the various interface inputs and outputs (including servos) which are either necessary or considered desirable. The table shows the signal designation, the number of bits required, and whether it is an input or output. The shutter control is used to open and close the shutter for printing control. The RUN lamp, error lamp/alarm, START switch, STOP switch, PROGRAM switch, and rate control are all signals associated with the control panel. The lens switch senses the position of the lens turret, and the shutter switch senses the position of the shutter. The limit switches sense the ends of travel of the various servo-driven mechanisms. The zero pulse signals indicate when the servo quantizers are at their zero pulse or reference positions.

Assuming interface hardware would be configured as 16-bit channels, Table 2-2 indicates that the interface would require 5 output and 2 input 16-bit parallel digital I/O channels. The 7 channels would provide 13 spare output command bits and 15 spare input sense bits for expansion. In addition, the backplane assembly which would be required to house the 7 channel cards has room for 8 cards, allowing for expansion to 8 channels.

2.4.2 Interface Hardware

The simplest approach to achieving computer control of the EOR is by utilizing servo logic cards, parallel input cards, and parallel output cards developed by Bendix Research Laboratories for control of

Table 2-2

EOR Interface Signals

Designation	Input/Cutput (I/O)	Bits
Print Drum Servo	0	12
Copy Platen Servo	0	12
Copy Carriage Servo	0	12
Lens Carriage Servo	0	12
Shutter Control	0	1
RUN Lamp	0	1
Error Lamp/Alarm	0	1
START Switch	I	1
STOP Switch	I	1
PROGRAM Switch	I	1
Rate Control Code	I	5
Lens Switch	I	1
Shutter Switch	I	1
Platen Limit Switch	I	1
Lens Limit Switch	I	1
Copy Limit Switch	I	1
Drum Limit Switch	I	1
Platen Zero Pulse	I	1
Lens Zero Pulse	I	1
Copy Zero Pulse	I	1

photogrammetric instruments. The servo logic card, which is described in Section C.5.1, is an integral part of the digital servo system. It receives 12-bit increments from the computer and meters them out to the servo. The rate metering of servo commands provided by this logic is important to the achievement of smooth servo operation. The parallel input and output cards provide signal conditioning for external devices. The parallel input card has circuitry which eliminates contact bounce noise. The parallel output card has lamp/relay driver circuitry, allowing direct connection to most indicator lamp and actuator circuitry.

The Bendix servo logic and parallel I/O cards are designed to plug directly into a DEC BB-11H prewired backplane assembly. Each of these backplane assemblies accommodates 4 channel cards, so 2 backplanes would be required for the 7 channels. For the DEC PDP-11/35 control computer, the UNIBUS cable plugs directly into the backplane assembly. Each backplane assembly has a DEC M105 address selector card for selecting the I/O channel and generating strobes.

To use the Bendix servo logic and parallel I/O cards with the Modcomp computer, additional equipment would be required. It would be possible to develop special logic circuitry which would connect to the Modcomp computer I/O bus and generate the necessary signals for the Bendix I/O cards, but this is not recommended because of the development cost. Interfacing to the Modcomp computer can be readily accomplished using standard Modcomp parallel digital I/O equipment in conjunction with the Bendix I/O cards. Using the Modcomp 1199-1 I/O Interface Subsystem with 1121-1 16-bit input, 1131 16-bit output channel cards, and an 1101 synchronizer card, data can be transferred to and from the Modcomp computer. A minimal amount of additional hardware (primarily for any necessary buffering or signal inversion) would then be required to connect the Modcomp I/O channels to the Bendix I/O cards. For the Modcomp system, the DEC BB-11 backplanes which hold the Bendix cards would be purchased blank (instead of prewired) and wiring would be installed between the backplanes and the Modcomp I/O channel cards. Since channel selection would be performed in the Modcomp I/O subsystem, the DEC M105 address selector cards would not be required. Strobe signals for transferring data from the Modcomp output channel cards to the servo logic and Bendix parallel output cards would be generated by the 1101 synchronizer card of the Modcomp I/O Interface Subsystem.

The technique for interfacing to the Nova computer would be similar to that of the Modcomp. A Data General 8311 Expansion Chassis would be connected to the Nova I/O bus. The expansion chassis would contain 6 standard Data General 4040 General Purpose Interface boards. Each of these boards has one 16-bit input and one 16-bit output channel. These Nova I/O boards would be connected to the DEC BB-11 backplanes which hold the Bendix cards. As with the Modcomp interface, the Nova interface would require a small amount of additional logic. The Nova general purpose interface boards, however, have board space available for mounting this logic, whereas the Modcomp would require separate cards.

2.5 SERVO DESIGN STUDY

Since the time when the present EOR servo systems were designed, significantly improved servo components such as motors, tachometers, and position encoders have become available. In addition, the techniques employed in the design of servo systems have shifted from analog to digital, with resulting improvements in accuracy, reliability, and noise immunity. The objective of the servo design study was to develop improved servo system designs for the EOR, based on the use of digital techniques and incorporating new servo components. Analysis and testing of the present servo systems were performed to determine their key characteristics. New servo systems were then developed utilizing the new technology, but retaining those components of the present servo system which are still useful. This section documents the design study for improving the EOR servo systems. Detailed descriptions of recommended servo systems appear in Appendix C.

2.5.1 Summary of Present EOR Servo Systems

The present EOR carriage and platen servo systems are essentially analog type servos. Position commands from paper tape are read and decoded into analog position and velocity command voltages which are applied to the servos. The position commands determine the correct positions of the three servos (copy platen, copy carriage, and lens carriage) for performing the desired rectification. The velocity signals are used to interpolate between successive positions and to provide velocity compensation for servo lag errors.

Position sensing is done with feedback potentiometers which generate voltages proportional to carriage or platen position. The potentiometers only indicate position within 1 in. of travel and repeat as the carriages are moved along successive 1 in. intervals. To avoid the discontinuity which would occur at the end of the potentiometer element, a dual position sensing potentiometer is used. The two sections of the dual potentiometer are arranged so that their ranges overlap. One section is used for the first 1/2 in. and the other section is used for the second 1/2 in. In addition to the position-sensing potentiometers, the present servos have compensation potentiometers for correcting carriage and platen errors along the entire length of their travel. These compensation potentiometers have about 60 taps, with each tap having an adjustable trimmer potentiometer. This provides for rather arbitrary correction of carriage and platen errors.

The drive motors presently used on the copy carriage, lens carriage, and copy platen are 10 W AC servo motors (Diehl FPE 25L-194-2AC). To provide sufficient torque to drive the large carriage assemblies, a 625:1 reduction gearbox is used (Pic ES-41). Tachometer feedback is generated with a DC tachometer generator (Barber Coleman FYLM 43920-51, 5 V per 1000 RPM) coupled to the motor through 1:1 gearing. The command carrier for the AC servo motor is generated in the servo power amplifier by chopping the DC input signal, and amplifying and filtering the resulting AC signal.

The mechanical drive mechanisms for the copy and lens carriages consist of steel tapes connected to the carriages, driven at one end by a 3.438 in. diameter pulley. Carriage position sensing is done with rack-and-pinion gears (nonbacklash) which drive the position potentiometer, compensation potentiometer, and position indicator synchro transmitter. The platen drive mechanism is a lead screw with a 0.1 in. pitch. Position sensing elements for the platen are gear-coupled to the lead screw.

The print drum of the EOR is presently driven by a synchronous motor with a vernier speed control servo system. Speed reduction is accomplished with a four-stage friction drive assembly. To compensate for velocity errors due to wear of the friction drive assembly, the housing of the synchronous motor is driven by a compensating velocity servo system. The speed of the compensating servo system can be adjusted to achieve the desired output drum velocity. The drum runs at a constant speed synchronized with the power line frequency. Although the drum can be operated at either 0.05 in. per second or 0.15 in. per second, it is presently operated only at the lower speed.

2.5.2 Servo System Tests

To determine certain important properties of the present EOR drive systems, experimental tests were made on the carriage, platen, and drum drive systems. The tests provided data upon which to base the design of the improved servo systems. The tests included servo dynamic response and backlash tests, torque requirements tests, carriage compensation requirements tests, and a print drum velocity test. The paragraphs which follow describe these tests along with test results and their implications about what improvements must be made.

2.5.2.1 Servo Response, Backlash, and Load Torque

To determine key parameters of the present EOR servo systems, measurements were made of the time domain response and backlash of the platen, lens carriage, and copy carriage servos. For the time response tests, the servo being tested was first placed in manual mode and displaced a small amount from the position commanded by the decoder. The servo was then placed in auto mode and allowed to settle. The error voltage of the servo was recorded on a chart recorder during the servo settling time. Such records produced by all three servos were subsequently analyzed to determine the servo time constants, which in turn were interpreted to be the reciprocals of the servo velocity constants. The results obtained are as follows:

Axis	Velocity Constant
Platen	7.2/sec
Lens Carriage	4.1/sec
Copy Carriage	1.7/sec

Backlash for the three servo systems was also measured. For the lens carriage, backlash of the position sensor was about 0.0006 in. For the copy carriage, position sensor backlash was about 0.0014 in. Backlash for the drive train gearing was also measured, and the results are as follows:

Axis	Drive Train Backlash
Platen	0.0005 in.
Lens Carriage	0.015 to 0.020 in.
Copy Carriage	0.011 to 0.020 in.

The platen backlash is fairly small compared with the lens and copy carriage backlash. For the lens and copy carriage backlash values, the smaller value was measured by applying a small amount of torque to the gear train. The larger value was obtained by applying large torque to the gear train. All drive train backlash measurements were made by holding the motor fixed and applying torque to the output member of the drive trains. Actual displacements of the various carriages were measured with an Ames gauge attached to the appropriate carriage.

The results of the servo response test show that the present EOR servos have significantly different velocity constants. In addition, the velocity constants are rather low, with the copy carriage velocity constant being extremely low. In the present EOR system, the differences in servo velocity constants are of little consequence because velocity compensation is applied to each servo to remove servo lag error. For the improved EOR, it was hoped that the servos could be matched in velocity constants so that velocity compensation would be unnecessary. Servo matching is usually accomplished by adjusting the tachometer feedback to increase or decrease damping. This approach offers little hope of success with the present EOR servos since the platen and lens carriage servos would have to be matched to the slower copy carriage servo. This would result in all three servos having unreasonably low velocity constants.

It may be possible to increase the velocity constant of the copy carriage servo by increasing the servo amplifier gain. The primary factor which would prevent such an approach is the large drive train backlash of the copy carriage. Increasing the gain may result in excessive gear chatter and perhaps instability. Since the lens carriage has about the same backlash as the copy carriage, however, it seems reasonable to expect that the velocity constant of the copy carriage could be increased to at least the present value of the lens carriage velocity constant (4/sec). This would be acceptable if the servos were not driven at speeds in excess of about 10 mm/sec.

The problem with servos having low velocity constant (Kv) is that the dynamic velocity error is large. This requires that the velocity constants of the three servos be very well matched. It also requires that a large digital error register and D/A converter be used in implementing digital servos. If the velocity constants of the servos cannot be significantly improved and matched, then velocity compensation must be employed in the improved EOR system to compensate for velocity errors. This is fairly easy to implement in the programs of the control computer. The most desirable approach, however, would be to replace the present gearbox with one having less speed reduction and consequently less back-lash. This would allow adjustment of the servos for higher Kv. It would require higher torque servo motors, but such motors are presently readily available.

To determine the torque requirements for new servo motors, the load torque of the lens and copy carriages was measured. The torque required on the tape drive pulley was determined by disconnecting the gearbox at its output shaft and measuring the force required to break-away and run the lens and copy carriages. The torque was then computed as the measured force times the drive pulley radius. The forces were measured with a spring scale and found to be rather high, probably because of worn ball bushings on the particular unit measured. The copy carriage required about 6 to 7 lb running with hard spots and break-away forces up to 10 lbs. The lens carriage required about 7 lb maximum with typical running forces of about 4 to 5 lb. The 10 lb maximum force converts to 275 oz-in. torque at the tape drive pulley shaft. With a modest gear reduction, this torque is well within the capability of present small torque motors.

In summary, the results of the servo response and backlash tests showed that there are large differences in the responses of the platen lens carriage and copy carriage servos. The velocity constants were also found to be rather low. Because of large backlash in the drive trains of the lens and copy carriages, it may not be possible to adequately match the servo responses with the present drive. Replacing the present gearbox with one having lower backlash would alleviate the problem. Velocity compensation in the computer can also be considered as a solution to the servo response mismatch problem. The torque required to drive the lens and copy carriages was found to be high, but is well within the capabilities of present small torque motors if gear reduction is used.

2.5.2.2 Carriage and Platen Position Corrections

The servo systems of the present EOR system incorporate compensation potentiometers to correct for errors inherent in the platen, lens carriage, and copy carriage. These errors are due to such things as lead screw pitch error, carriage position sensing error, and modeling errors resulting from lens characteristics. The platen has one compensation potentiometer, and the lens and copy carriages each have two compensation potentiometers; one for the 7.85 in. lens and another for the 14 in. lens. Associated with each compensation potentiometer is a set of about 60 trimmer potentiometers, each connected to a particular tap on the compensation potentiometer. These trimmer potentiometers provide rather arbitrary corrections to be added to the sensed carriage position at regularly spaced points along the carriage travel.

The improved EOR system will not use the compensation potentiometers. Instead, the carriage and platen errors will be compensated in the computer programs. The positions commanded by the control computer will then be corrected for errors and hardware corrections will not be required.

To determine the magnitude and nature of the corrections presently applied to the EOR platen and carriages, measurements were made of the error voltages across the various compensation potentiometers at uniform intervals. This information was used to indicate the computer programs which would be required on the improved EOR system to correct for carriage and platen errors. The voltage measurements were converted to their equivalent positional corrections in inches, and least-squares linear regression analyses were performed on the data. The regression analyses determined linear trends and residuals of the error data sets.

The analysis results are shown in Table 2-3. The standard deviation values shown in the table indicate the error which would remain if only simple linear scaling and offset corrections were used to correct position errors. The residual platen error (0.00037 in. rms) is fairly small, indicating that simple scaling and offset correction might be sufficient for the platen axis. The residual platen errors, as shown in Figure 2-3, are also rather random, indicating no significant higher order systematic effects.

Residual errors for the lens carriage and copy carriage are rather large, as can be seen from the standard deviations in Table 2-3. Figures 2-4 through 2-7, showing plots of these residual errors, indicate that the present corrections are of rather high order also. Figure 2-7 shows two discontinuities in the present compensation for the copy carriage with 14 in. lens. This, however, may only mean that the present compensation is not properly adjusted for this axis.

The results of compensation potentiometer voltage measurements and subsequent analyses indicate that tabular corrections will be required in the improved EOR system for at least the copy and lens carriages. It may, however, be possible to use fewer than 60 table entries if break-points are selected judiciously. The plots of Figures 2-4 through 2-7 show that present corrections are fairly linear between the various break-points in the curves.

Table 2-3

Compensation Voltage Analysis Results

Axis	Linear Trend (in./in.)	Standard Deviation (in.)
Platen	0.0005543	0.00037
7.85 in. Lens Carriage	0.0015719	0.00542
14 in. Lens Carriage	0.0014540	0.01544
7.85 in. Copy Carriage	0.0014476	0.00765
14 in. Copy Carriage	0.0006259	0.02206

2.5.2.3 Drum Velocity and Torque Tests

Samples of output film from the present EOR system exhibited striations in the direction of the slit aperture. The source of these striations was initially thought to be variations in print drum velocity. To test this hypothesis, a test was performed on the EOR system (Unit 4) to determine drum velocity variations. A light chopper driven by a synchronous motor was attached to the copy platen. This light chopper modulated the light from the slit to provide pulses of light at regular time intervals. For the test, the copy carriage and lens carriage were initially positioned for 1X magnification and then held fixed throughout the test. The print drum was allowed to run normally at the slow (5 Hz) speed.

The printed output film showed the expected line structure (due to the light chopping) with a nominal line spacing of about 42 μm. Variations in line spacing were observed, and generally where there were line spacing variations, adjacent open areas of the film showed striations. Although it was originally thought that the line spacing variation was due to drum velocity variation, closer examination of the film revealed that the line spacing variations are not constant along the direction of the slit. If the line spacing variation was due entirely to drum velocity variation, it would be constant across the entire length of the film.

From the results of the drum velocity test it was concluded that something other than, or in addition to, drum velocity variation is causing the vertical striations in the film. It may be that localized fluxuations in light output of the mercury vapor lamp is causing the striations. It is also possible, but not very likely, that the drum wobbles. Another possibility is that some critical component of the optical system such as the optical slit is vibrating. In conclusion, it is expected that replacing the present drum drive system with a servo system will not entirely eliminate the vertical striations in the output film. There are still, however, good reasons for wanting to replace the present drum drive system.

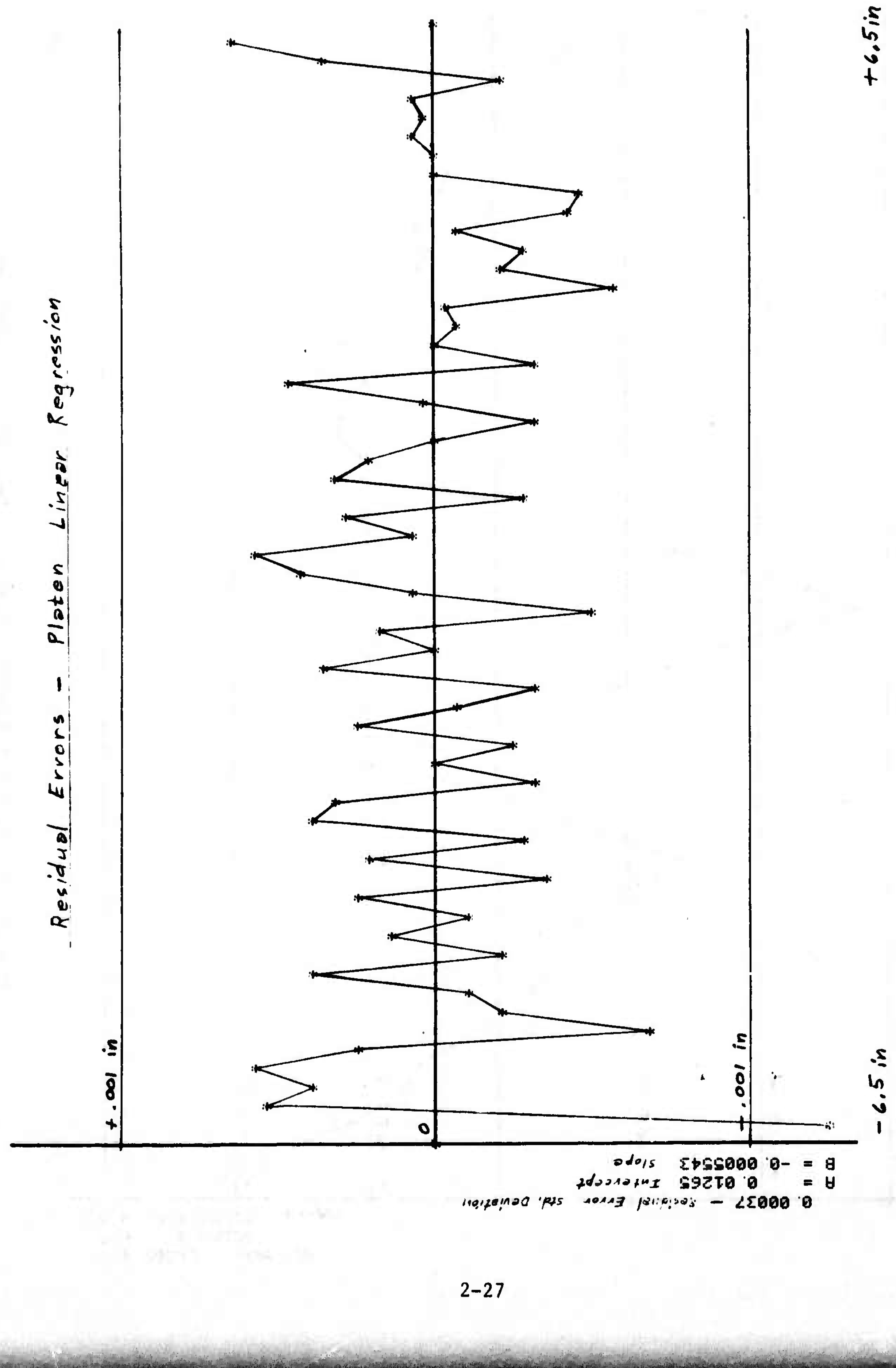

Figure 2-3 - Residual Errors - Platen Linear Regression

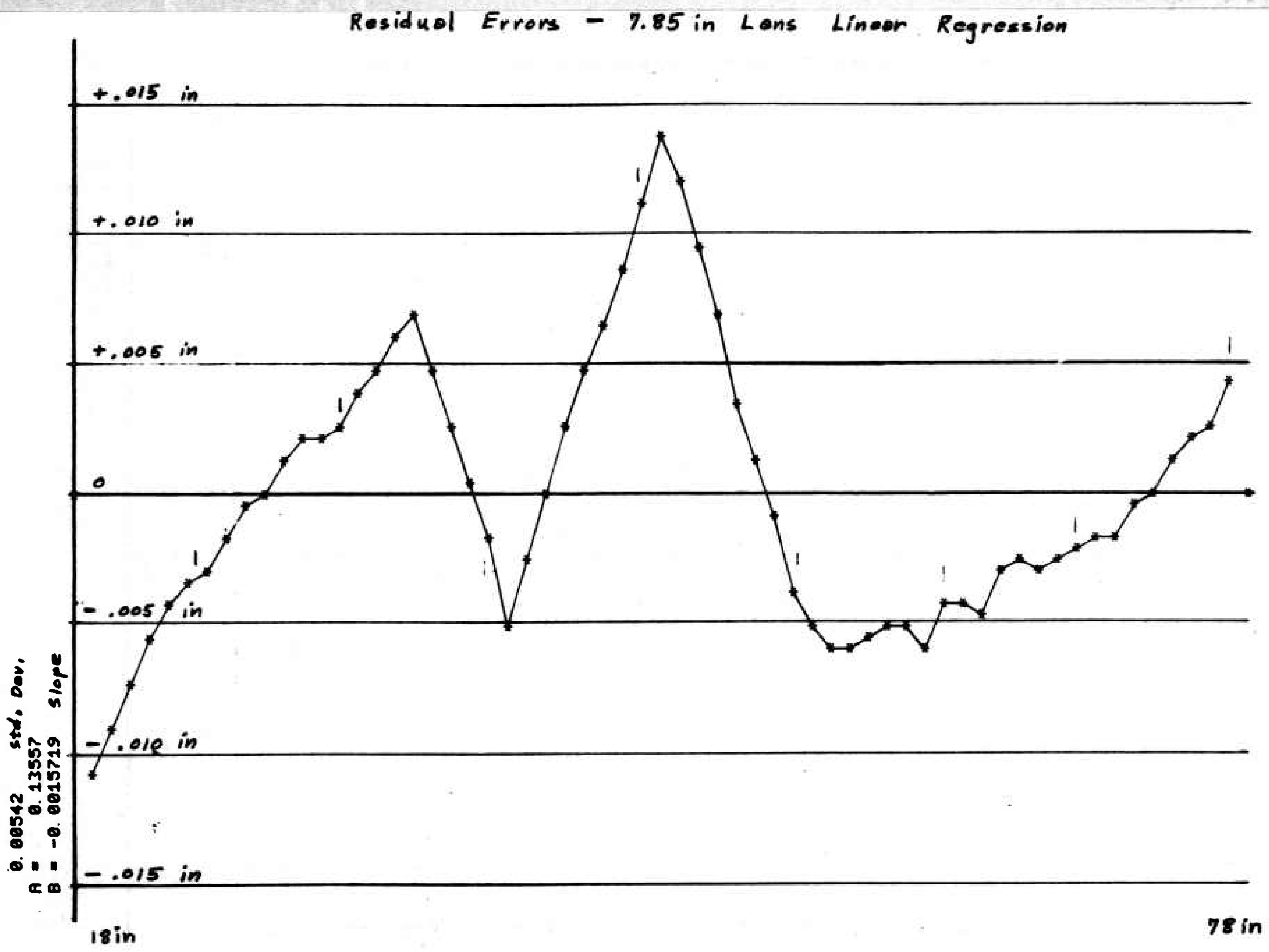

Figure 2-4 - Residual Errors - 7.85-Inch Lens Linear Regression

Figure 2-5 - Residual Errors - 14-Inch Lens Linear Regression

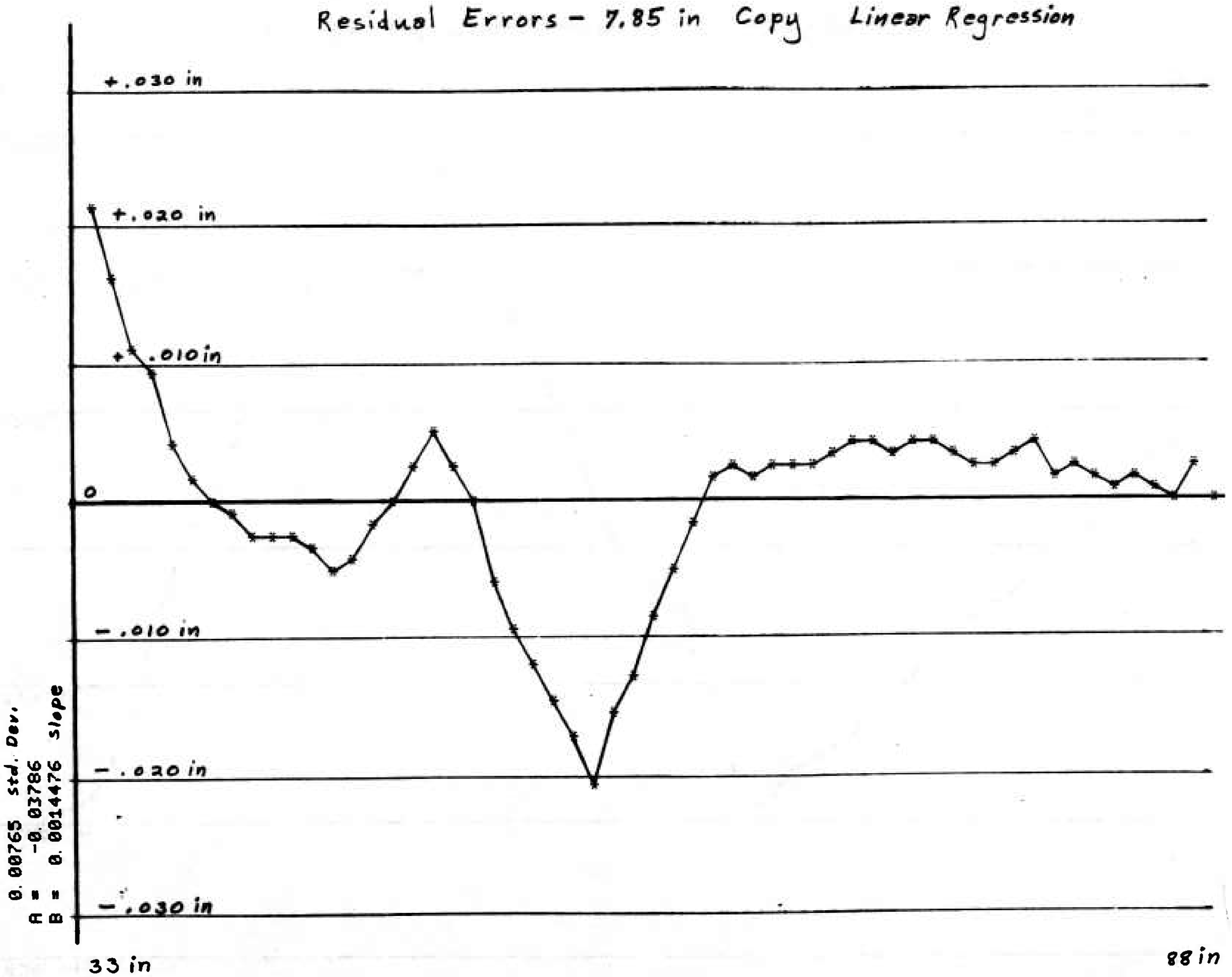

Figure 2-6 - Residual Errors - 7.85-Inch Copy Linear Regression

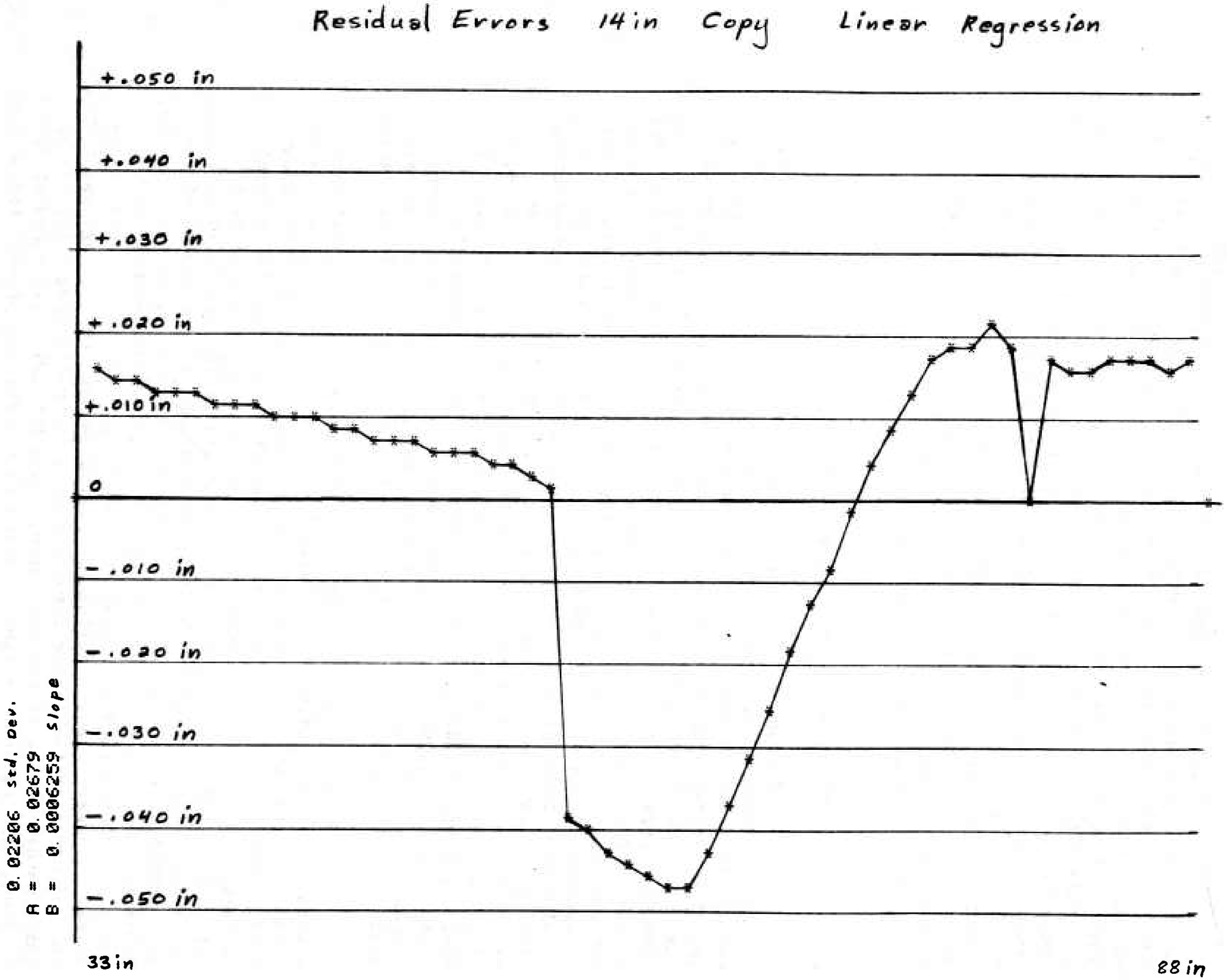

Figure 2-7 - Residual Errors - 14-Inch Copy Linear Regression

Measurements were made of the torque required to start and run the EOR print drum. These measurements were made on both Unit 3 and Unit 4. It was found that the torque required to move the drum forward was about two to three times as much as was required to move it in the reverse direction. The torque required for starting was about the same as required for continuous motion. It was about 80 to 130 oz-in. in the forward direction and 40 oz-in. in the reverse direction. This is somewhat higher than expected, but will not be a significant problem in the improved system. The fact that the drum turns easier in one direction than the other offers some hope that it may be possible to reduce the drum friction somewhat. Also, in the improved system the drum will be servo-driven and can be run in either direction for printing, allowing operation of the drum in its easy direction.

2.5.3 Servo Improvement Recommendations

Although it may be possible to use the present carriage and platen servo motors, amplifiers, and gearboxes in a digital servo system, it is recommended that these components be replaced. The low velocity constants of the present carriage servos cause large dynamic lag errors which are difficult to compensate and result in large residual dynamic errors. For the EOR servos, which can be characterized as basic first-order systems, a constant servo error exists whenever the servos are running at a constant velocity. This error is proportional to the reciprocal of the velocity constant (Kv), so a low velocity constant results in a large error. The large error makes velocity compensation difficult because of a large sensitivity to component tolerances. Sensitivity to tachometer errors is a particularly undesirable consequence of a low velocity constant. Because of high drive train backlash, it would probably be difficult to increase the velocity constants of the present servos without incurring problems with gear chatter and/or instability. This means that if the present servo drive systems were used for the digital servo system, dynamic performance would be limited.

Unlike the present analog servo system, a digital servo system has a limitation on how large the servo lag error can be. A reasonable limitation on the size of the digital error register is about 12 bits. This is based on the fact that larger digital-to-analog (D/A) converters are much more expensive. Assuming a least significant bit represents 1/10,000 in. the servo error would be limited to ±0.2048 in. For a low velocity constant such as the present 1.7 per second of the copy carriage, this would severely limit the maximum velocity. (That is, 0.348 in./sec. for the copy carriage.) This is unacceptable for the digital system, primarily because of the large time which would be required for servo slewing during initialization of the carriage positions. The influence of tachometer errors on dynamic positioning error can be quite severe if lag errors are large. At a typical servo speed of 0.05 in./sec, the tachometer ripple, which is ±3% for the present tachometer, could cause dynamic positioning errors of up to ±0.0008 in.

In addition to the limitations of the present carriage servos mentioned above, there are other reasons for replacing the servo drive components. From the recent maintenance history of the EORs, it appears that replacement of tachometers has been quite frequent. New servo motors and tachometers which run at lower speeds would reduce such maintenance. The present AC motors are rather small and become quite hot during normal operation, suggesting that they may be stressed. Finally, because of the obsolete nature of the AC servo motors and other components it may be difficult in the future to obtain replacements.

Because of the performance limitations and other shortcomings of the present servo components, they should be replaced with new, higher performance components. Use of new low speed, high torque DC motors will allow the carriages to be driven with less gear reduction and consequently less backlash. This will allow the servos to be adjusted for a higher velocity constant, resulting in increased speed capability and lower dynamic errors. The present reduction gearbox, which has a ratio of 625:1, should be replaced with one having a ratio of about 25:1. New tachometers which can be obtained as an integral part of the new DC servo motor offer lower ripple (1%) and longer life. Replacement of the AC servo motors with high torque DC servo motors will require that new servo power amplifiers be used also. Although the platen servo presently has adequate response, it should also be replaced because of obsolescence, the heating problem, the tachometer replacement problem, and to make it compatible with the other new servos.

The drum velocity test did not conclusively implicate the present drum drive system as the source of striations in the output film. Replacing the drum drive will not, therefore, eliminate that problem. There are, however, other reasons for wanting to replace the drum drive. A major reason for replacing the present fixed speed drive with a servo drive system is that the print speed could be controlled in an arbitrary manner from the computer. This would allow increasing the exposure of the film by running the drum at a slower speed. Variable speed could also be used to compensate for effects which cause exposure to vary across the output film. Replacing the present drum drive would, therefore, improve the capabilities of the EOR system to accommodate slower speed films and achieve more uniform exposure across the photograph.

Another reason for replacing the drum drive is that the present one is mechanically complicated and subject to wear, causing high maintenance. As the rollers in the present friction drive assembly wear down, the vernier velocity servo must be periodically adjusted to compensate. Occasionally, various parts of the friction drive assembly must be replaced as they wear out. It is recommended that the present drum drive assembly be replaced with a direct drive DC torque motor and tachometer, with inductosyn position sensing. This will provide arbitrary computer control of the drum speed and will reduce maintenance.

2.6 OPTICAL COMPONENTS STUDY

The study of optical components of the EOR system had two basic objectives. These were:

(1) To increase light levels in the system.

(2) To be able to cover a magnification range of 0.6X to 6X with a single lens.

The first objective is desirable because more light in the system will allow use of slower, high resolution films. This objective, however, loses much of its significance if the print drum of the improved EOR system is servo-controlled. The servo-controlled print drum allows arbitrary control of print velocity, and exposure time can be increased by just reducing print velocity. Nevertheless, some study effort was devoted to achieving this objective with optical component modifications. This effort included a survey of some larger aperture lenses, an investigation of possible arc lamp improvements, and consideration of condenser optics redesign.

To meet the second objective, carriage travel distances and lens focal length were determined for covering the 0.6X to 6X range. Literature on off-the-shelf lenses was then searched for a suitable lens. In the paragraphs which follow, results of study work on lenses and light sources are presented.

2.6.1 Single Lens for 0.6X to 6X Range

During technical discussions with DMAAC personnel early in the study program, a desire was expressed to be able to cover the magnification range of 0.6X to 6X with a single lens. This possibility was studied and found to be feasible; however, it requires some modifications to certain EOR mechanical components. It was determined that a 10-3/4 in. focal length lens which is available could be used if the travel ranges of the copy and lens carriages could each be extended by about 1 in.

To achieve a magnification of 0.6X with the 10-3/4 in. lens, the lens carriage must be able to reach 17.2 in. distance from the drum. The present nominal lower limit of lens carriage travel is 18 in., so the lower limit must be extended by about 1 in. This can be achieved by modifying the present lens mounting. The face on which the lens flange rests could be machined down 1 in. to move the lens 1 in. closer to the drum at the lower limit of lens carriage travel. A potential problem which may arise from this is that the lens barrel may protrude into an area where it would interfere with lens turret motion. With the single lens covering the entire desired range, however, this may not be objectionable.

It was determined that a copy carriage distance of about 88.8 in. was required (assuming a lens nodal distance of 1 in.) to achieve 6X magnification with the 10-3/4 in. focal length lens. Although the present copy carriage is nominally supposed to cover this distance, it does not because of a cable mounting bracket. Moving this bracket will allow approximately 89 in. of distance between the copy carriage and drum. This will be sufficient to achieve 6X optical magnification.

Specifications for the 10-3/4 in. lens are shown in Figure 2-8. This lens is presently available from Rolyn Optics, 300 Rolyn Place, Arcadia, California. At the time of inquiry, they had three in stock. Since the lens was not tested, it is not clear whether or not the lens would provide better resolution than the present lenses. To determine the performance of this lens in the EOR application it should be installed in the EOR and tested.

Focal Length	**10-3/4 in.**
Tolerance on Focal Length	**±1%**
Aperture	**6.3**
Field Angle	**70°**
Coverage	
1:1	**18 in. x 22 in.**
Infinity	**8-1/4 in. x 10-1/2 in.**
Resolving Power	**100 - 150 1p/mm**
Coating	**Hard anti-reflection coatings on all glass-to-air surfaces**
Mounting	**Black anodized aluminum barrel with iris diaphram and mounting flange**
Manufacturer	**Rank/Wray Optical**

R-276-6

Figure 2-8 - 10-3/4 Inch Lens Specifications

2.6.2 Other Replacement Lenses

A survey of presently available process lenses was conducted to determine if lenses which are similar to the present ones in focal length but larger in aperture could be obtained. The present lenses are Goertz Artar Red Dot process lenses with f/9 aperture. One lens is 7.85 in. focal length and the other is 14 in. focal length. A list of possible replacement lenses which were found appears in Table 2-4. The table shows focal length, aperture size, and magnification range which could be covered using the present EOR carriage travel limits. These lenses are also available from Rolyn Optics. Included in the list is the 10-3/4 in. lens which was discussed in Section 2.6.1. The range given for this lens assumes modification of the EOR. Performance of these lenses in the EOR application would have to be determined experimentally.

Table 2-4

Possible Replacement Lenses

Focal Length	Aperture	Magnification Range
10-3/4 in.	6.3	0.6X to 6X *
8 in.	5.6	1.25X to 8.75X
8-3/4 in.	6.3	1.06X to 7.82X
8-1/2 in.	6.3	1.12X to 8.11X
15 in.	3.5	0.28X to 3.52X

*Requires modification of EOR to cover this range.

2.6.3 Recalibration

Because the calibration mechanism will be different for the improved EOR system (software rather than hardware) it will be necessary to recalibrate the system. If a new lens is selected, the exact focal length and rear nodal distances will have to be determined using a lens bench equipped with a nodal slide. After these lens parameters are determined, recalibration can be achieved by making linear enlargement runs at various magnification points to determine magnification errors. These errors can then be related to carriage position errors to determine necessary corrections. At each of the magnification points, resolution targets can be copied with various perturbations of the carriages to determine position corrections for optimum focus. The final corrections must be determined by striking some balance between geometric fidelity and resolution since the corrections may not be the same for optimizing both simultaneously. After corrections at the selected magnification points are determined, corrections between these points are determined by linear interpolation.

2.6.4 Light Source and Condenser Optics

In the study, the possibility of achieving more light output from the light source and condenser was investigated. It was also considered desirable to investigate light sources which would provide better color reproduction. The following paragraphs discuss results of these investigations.

The light source presently used in the EOR is a 2 ft mercury arc lamp manufactured by Hanovia Chemical and Mfg. Co. (Model DL-5047-27v). It is rated at 120 W/in., and the entire unit is rated at 3000 W. Discussions with a representative of the manufacturer revealed that a higher wattage lamp rated at 200 W/in. is available. Use of this higher wattage lamp in the EOR would require a new lamp power supply. The increased heat generated by the lamp may also cause heating problems in the lamp housing and condenser optics. Use of the higher voltage lamp is, therefore, not recommended.

Depending upon the spectral sensitivity of the film used, it may be possible to increase exposed film density by using a modified light source of the same (3 kW) rating. By doping the mercury lamp with certain metal halides, the positions of certain spikes in the spectrum of the mercury vapor lamp can be moved from the region of 200 to 300 nm to 300 to 400 nm. This moves more output power to a part of the spectrum where the film is probably more sensitive. A spectral energy distribution plot of a typical undoped mercury lamp is shown in Figure 2-9. As can be seen in the plot, the amount of energy in the spikes is quite high.

The use of a xenon lamp to achieve better color reproduction is not recommended. From Figure 2-10, which is a spectral energy distribution plot of a xenon lamp, it can be seen that the lamp output is very high in the infrared region. This could cause severe heating problems and may, in fact, damage the condenser optics. Since the exposure on the improved system can be controlled by running the print drum slower, a better (or at least safer) approach to improved color reproduction is to use compensating filters with the present mercury lamp.

Modification of the condenser optics and/or lamp housing to achieve more light through the system does not appear to be a reasonable thing to do. It would be very expensive and would probably not significantly increase light output. If light was reflected from the unused side of the lamp back to the slit, it would have to come to a focus at the plasma. It is not likely that a significant amount of this reflected light would get through the plasma. The reflected light could, of course, be imaged alongside of the lamp plasma, but significant problems exist with this approach also. Such problems include need for a redesign of the condenser optics and a need for good lamp image alignment so as not to create a shading problem along the length of the slit.

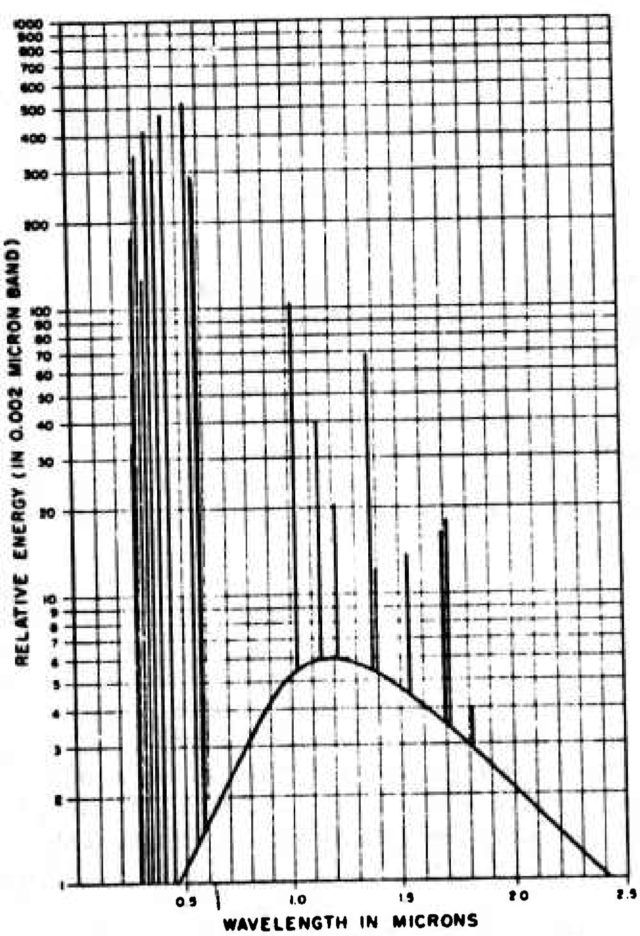

Figure 2-9 - Spectral Energy Distribution of Mercury Arc Lamp

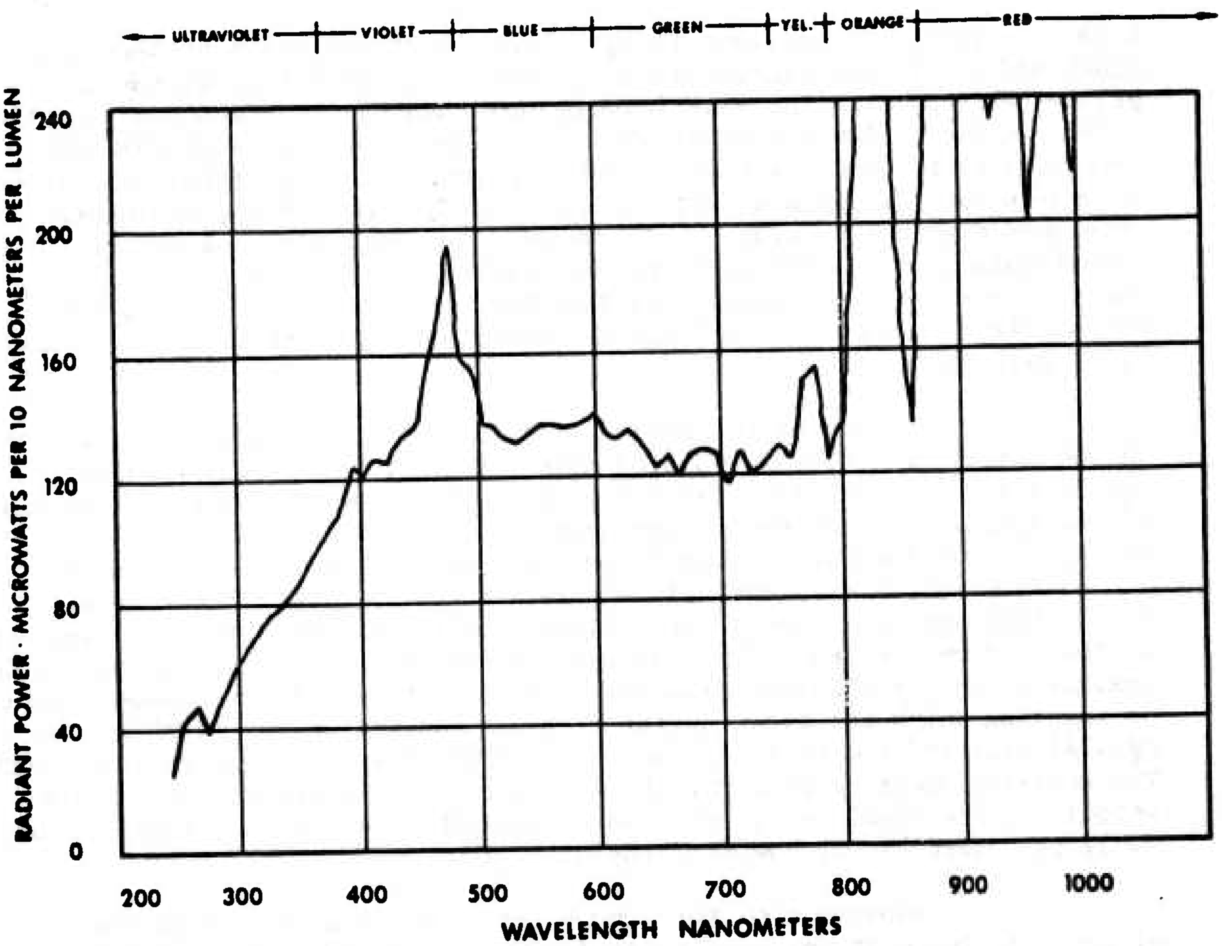

Figure 2-10 - Spectral Energy Distribution of Xenon Arc Lamp

2.7 MATHEMATICAL ANALYSIS

As part of the overall EOR system study, several mathematical analyses were performed to determine the relationships between certain EOR system characteristics and system performance parameters. To determine whether or not light through the system could be increased by increasing slit width, an analysis of the relationship between slit width and resolution was performed. An analysis of the effects of carriage position errors on resolution was also performed. This analysis considered both the present f/9 lenses and the possible replacement f/6.3 lens. The relationships between carriage and platen positioning accuracy and geometric errors in the printed output were also investigated.

2.7.1 Effect of Slit Width on Resolution

The present EOR has a slit width of about 10 μm. If the width of this slit could be increased without seriously affecting resolution, more light could be passed through the system, resulting in an increased exposure capability. To determine if a larger slit could be used, a mathematical analysis was performed to establish the relationship between slit width and resolution degradation. Typical limiting values of the appropriate parameters of the relationship were then applied, and the resulting effect on resolution was determined. The results of the analysis indicate that increasing print slit width can have a rather disasterous effect on resolution for certain rectification situations. It is, therefore, not recommended that slit width be increased. The analysis included an investigation of how EOR performance is affected by the finite slit width at various sweep angles for panoramic rectification. The paragraphs which follow present the analysis of resolution degradation due to finite print slit width.

Because of the finite width of the EOR optical slit, a point on the output drum is exposed over some period of time. This period is equal to the time required for the point to traverse the width of the image of the optical slit on the output drum. In the EOR system, the slit width is determined at the input, so the width of the slit image on the output drum varies with optical magnification. In general, the velocity of the photographic image at the output drum is different from the velocity of the film on the drum. The photographic image, therefore, can move with respect to the film during exposure. The amount of relative image motion or smearing which can occur during exposure depends on the width of the optical slit and the ratio of the photographic-image-to-film velocity ratio. The smearing occurs only along the direction of film travel, and if the velocities are equal (as in the case of simple enlargement), there is no smearing regardless of how wide the slit is.

Exposure time for some point on the drum is simply the width of the slit image at the output divided by the output film velocity:

$$T = \frac{W\ Mu}{Vo}$$

where:

- W is the width of the slit at the input
- Mu is the optical magnification
- Vo is the velocity of the output film on the drum

The smear distance for imagery printed on the film is equal to the difference in velocity of the photograph image at the output plane and the output film, multiplied by exposure time

$$d = (V_I - Vo)\,\frac{W\ Mu}{Vo} = W\ Mu\left(\frac{V_I}{Vo} - 1\right)$$

where:

d is the smear distance

V_I is the velocity of the photograph image at the output plane

The velocity ratio V_I/Vo is equal to the ratio of optical magnification to velocity magnification (Mv):

$$\frac{V_I}{Vo} = \frac{Mu}{Mv}$$

So the smear distance can be expressed as

$$d = W\,Mu\left(\frac{Mu}{Mv} - 1\right)$$

The effect of uniform image motion during exposure can be expressed as a modulation transfer function (MTF) operating on the input image. This transfer function affects only the coordinate v which lies along the principal line of the photograph, and is given by (see Appendix A for derivation)

$$MTF = \frac{\sin\left(\frac{\omega_o d}{2}\right)}{\left(\frac{\omega_o d}{2}\right)}$$

Where ω_o is the spatial frequency of imagery at the output plane. Substituting the expression for d and using $\omega_o = \omega/Mu$ to refer spatial frequency to the input photograph gives

$$MTF = \frac{\sin\left[\frac{\omega W}{2}\left(\frac{Mu}{Mv} - 1\right)\right]}{\left[\frac{\omega W}{2}\left(\frac{Mu}{Mv} - 1\right)\right]}$$

From the relationship it can be seen that when Mu = Mv, no resolution degradation occurs. This is not the case in general for oblique frame or panoramic photography except at one point along the principal line of the photo. To illustrate the effects of a finite slit width on resolution for panoramic rectification, MTF was plotted for magnification ratios which occur at various sweep angles. These plots are shown in Figure 2-11. The plots show that resolution is only slightly affected at θ = 40 deg. At θ = 60 deg, the degradation becomes significant, and at θ = 80 deg, frequency components above about 70 cycles/mm are greatly attenuated.

To show the effects of changing slit width on resolution, MTF plots were made for 5, 10, and 20 μm slit widths. These plots are shown in Figure 2-12. A magnification ratio of 0.111 was used for the plots, representing a typical worst case for oblique frame and vertical panoramic geometries. The plots show that increasing the slit from the present 10 μm to 20 μm would have a disasterous effect on resolution under this worst-case condition. Figure 2-13 shows how a panoramic rectification would be affected at various scan angles if the print slit width were increased to 20 μm. The degradation is not serious for small sweep angles, but is rather severe for large sweep angles. Increasing the slit width of the EOR is, therefore, not recommended.

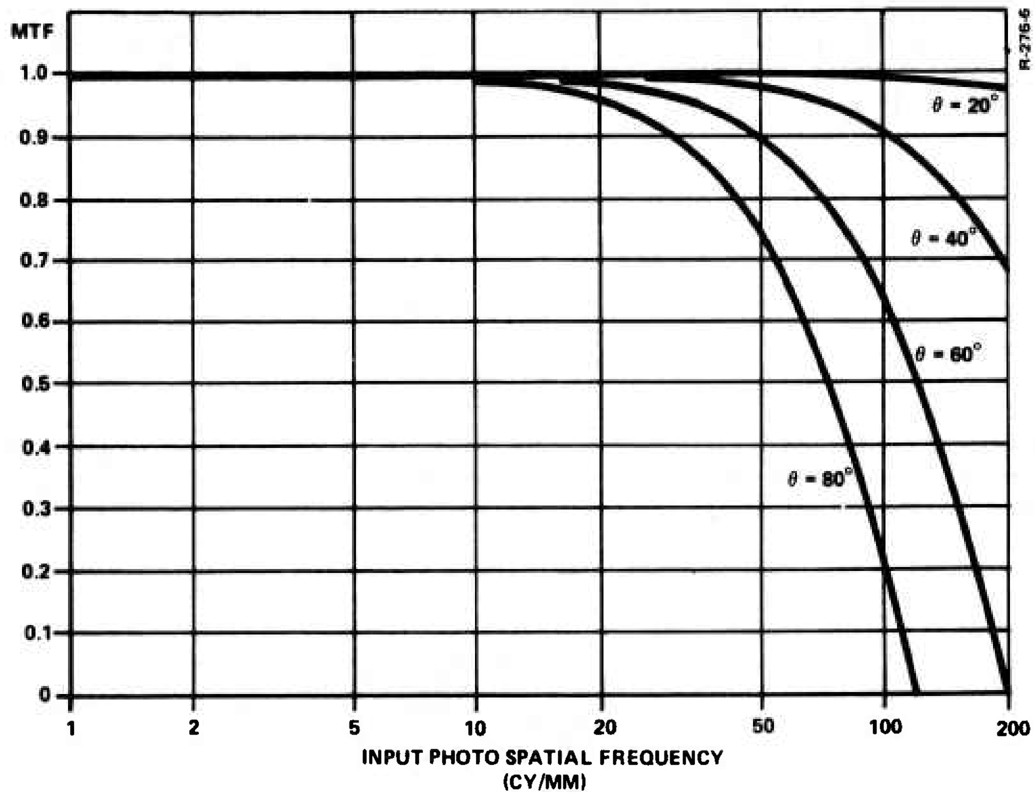

Figure 2-11 - Resolution Degradation Due to 10 μm Print Slit Width for Panoramic Rectification at Various Scan Angles (θ)

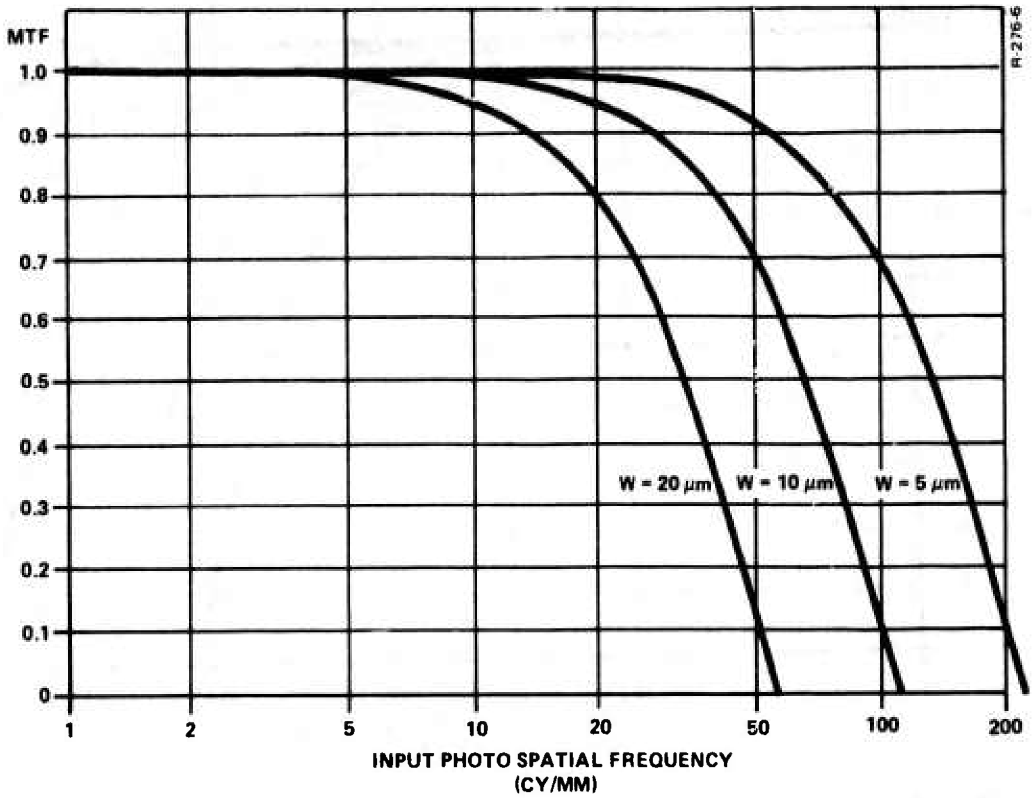

Figure 2-12 - Resolution Degradation Due to Print Slit Width at Mu/Mv = 0.111

2.7.2 Effects of Carriage Position Errors on Resolution

To obtain best resolution from the EOR system, the copy carriage and lens carriage should be positioned exactly according to the autofocus relationships. Any positioning errors of the lens and copy carriages will misfocus the system and degrade the resolution. The amount of positioning error which can be tolerated depends on the depth-of-focus and depth-of-field of the optics. For a blur circle of diameter c appearing at the output of the system, the depth-of-field and depth-of-focus relationships are

$$\delta o = \pm\, cf\# \left(\frac{M+1}{M^2}\right) \quad \text{(depth-of-field)}$$

and

$$\delta i = \pm\, cf\# \,(M + 1) \quad \text{(depth-of-focus)}$$

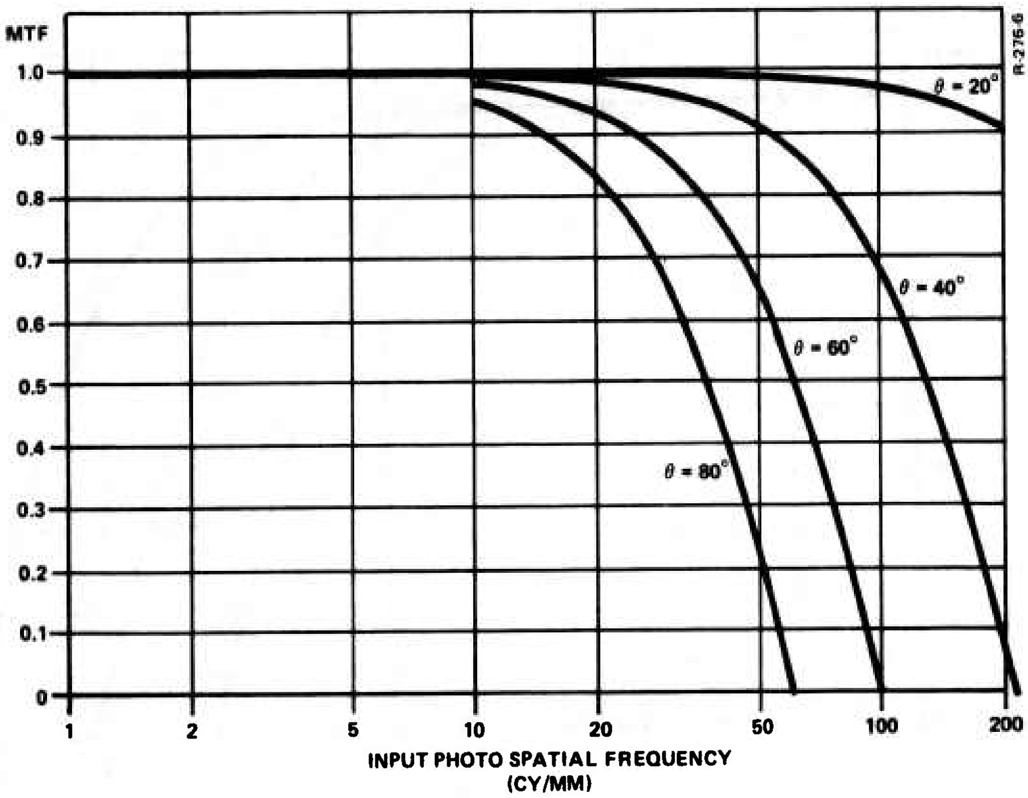

Figure 2-13 - Resolution Degradation Due to 20 μm Print Slit Width for Panoramic Rectification at Various Scan Angles (θ)

where

c is the blur circle at the output

f# is the number of the lens

M is the magnification

If the criterion for depth-of-field and depth-of-focus is such that the blur circle c must equal the Airy disk size for the lens, the above equations are modified by substituting

$$c = 2.44\ \lambda f\#\ (M + 1)$$

which is the size of the Airy disk at the output image plane. In this equation, λ is the wavelength of light. Making the substitution, the depth-of-field and depth-of-focus equations become

$$\delta o = \pm\ 2.44\ \lambda (f\#)^2 \left(\frac{M+1}{M}\right)^2 \quad \text{(depth-of-field)}$$

$$\delta i = \pm\ 2.44\ \lambda (f\#)^2\ (M + 1)^2 \quad \text{(depth-of-focus)}$$

The worst-case situation occurs at maximum magnification, where the depth-of-field becomes smallest. Table 2-5 shows values of δo and δi for a variety of conditions. The f/9 lens is the one presently used on the EOR. Maximum magnification for the present system is 9X. The f/6.3 lens is for a new lens which would allow magnification up to only 6X. For these calculations, λ was assumed to be 0.4 μm.

Table 2-5 - Typical and Worst-Case
Depth-of-Field and Depth-of-Focus Values

Lens f#	Magnification (M)	Depth-of-Field (δo)	(Depth-of-Focus (δi)
9	1	± .0124 in.	± .0124 in.
9	9	± .0038 in.	± .3112 in.
6.3	1	± .0061 in.	± .0061 in.
6.3	6	± .0021 in.	± .0747 in.

The table shows that if a new lens with larger aperture (smaller f#) is used in the improved EOR, carriage positioning accuracy requirements will be more stringent. The worst situation occurs at M = 6 for the f/6.3 lens, where the depth-of-field is about ± 0.002 in. This represents the worst-case tolerance on the object distance. Since the object distance is determined by both the lens carriage position and the copy carriage position, the tolerance on the carriages should be ± 0.001 in. to allow for the worst-case situation.

The data in Table 2-5 does not show the comparative reduction in depth-of-field and depth-of-focus from the f/9 lens to the f/6.3 lens in terms of constant resolution degradation. This is because the size of the Airy disk was used as a criterion, and the size of the Airy disk for the f/6.3 lens is smaller than that of the f/9 lens. If the depth-of-field and depth-of-focus for the f/6.3 lens are computed on the basis of a blur circle having the same size as the Airy disk for the f/9 lens, the values obtained for δi and δo at M = 1 (δi = δo) are 0.0087 in. for the f/6.3 lens compared with 0.0124 in. for the f/9 lens. On this same basis, at M = 6, the f/9 lens would have a depth-of-field of 0.0042 in. and the f/6.3 lens would have a depth-of-field of 0.0030 in. for equivalent resolution degradation. The carriage position tolerance could therefore be relaxed to ± 0.0015 in. if the resolution degradation for the f/6.3 lens is allowed to be as large as that of the f/9 lens. In this case, the primary advantage of using the larger aperture lens would be increased light through the system. Significant resolution improvement would be obtained only when carriage position errors are small.

2.7.3 Geometric Error

The geometric fidelity specification for the EOR requires that printed output points must be within a circular error of 0.01 in. (250 μm) of their theoretically correct position for optical magnifications up to 9X and scan magnifications up to 12X. Above scan magnifications of 12X, the error must not exceed 0.04 in. (1 mm). The first part of the specification implies carriage positioning accuracies of:

Copy Platen	$\pm$ 0.00059 in.
Copy Carriage	$\pm$ 0.00162 in.
Lens Carriage	$\pm$ 0.00162 in.

The second part of the specification (0.04 in. error for scan magnification above 12X) is not specific enough to determine how accurate the copy platen must be. Position errors in the scan direction are directly proportional to scan magnification. Since there is no specific limitation on scan magnification, the positioning accuracy requirement for the copy platen could become unreasonably severe.

As indicated by the above values, the copy platen positioning accuracy is the most important. The required copy platen accuracy is determined by assuming the 0.01 in. circular error is divided evenly between the two output coordinates (for the case where scan magnification does not exceed 12X). The required copy platen tolerance ε_v is then determined by:

$$|\varepsilon_v| < \frac{0.00707 \text{ in.}}{\text{scan magnification}}$$

For the 12X scan magnification, this requires that $|\varepsilon_v| < 0.00059$ in. This is slightly less stringent than the 0.0005 in. specification indicated in the Fairchild Proposal No. SME-CG-47, 1 February 1965. Since the oblique frame test extends to a scan magnification of 11X, it is assumed that the present system can meet this specification. A better test of this critical scan magnification error would be to run a linear rectification at 12X in the scan direction. Because the scan magnification error is so dominant, it is probably desirable to replace position sensor gears in the copy platen drive with nonbacklash gears to minimize platen position errors.

The error tolerance indicated above for the copy platen must include both static positioning errors and uncompensated dynamic errors. With the improved servos, the dynamic errors would be less than 0.0002 in. for velocities normally used in the EOR; leaving a budget of 0.00055 in. for static errors. The static and dynamic errors of the print drum also affect accuracy in the scan direction. Since they appear at the output, however, their contribution is negligible.

The effects of lens carriage and copy carriage position errors on output position errors are determined by analysis of the basic optical magnification geometry as illustrated in Figure 2-14. In the figure, q represents the lens carriage position and L represents the copy carriage position. From the geometry, the output position (X) of a point (x) on the input photograph is given by

$$X = x \frac{q}{L-q-N}$$

If L and q are treated as the independent variables, taking the total differential of X gives

$$dX = x\left[\frac{(L-q-N)\ dq\ -\ q(dL-dq)}{(L-q-N)^2}\right]$$

which can be reduced to

$$dX = x\left[\frac{(p+q)\ dq\ -\ qdL}{p^2}\right]$$

This relationship suggests that the errors subtract, but since dq and/or dL could be positive or negative, the terms must be added to get the worst-case error. Noting that q/p is the magnification, and replacing the differentials by the appropriate ε error symbols, the maximum output error ε_X is given by

$$\varepsilon_X = \frac{x}{p}\left[(M + 1)\ \varepsilon_q + M\ \varepsilon_L\right]$$

Optical magnification position error is seen to be dependent on optical magnification and the distance (x) from the optical axis to the point. The error is worst for large magnification and large x. In the present EOR system, maximum M is 9X. At this magnification, the output format limits x to 2 in. Assuming ε_q and ε_L are equal, the tolerance for carriage positioning error ε is

$$|\varepsilon| < \frac{0.00707}{\frac{x}{p}\ [2M + 1]}$$

which for the present system (7.85-in. lens) is $|\varepsilon| < 0.00162$ in. If the present lenses are replaced by a single lens with a focal length of 10.75 in., the required tolerance would be $|\varepsilon| < 0.00227$ in. which is less stringent.

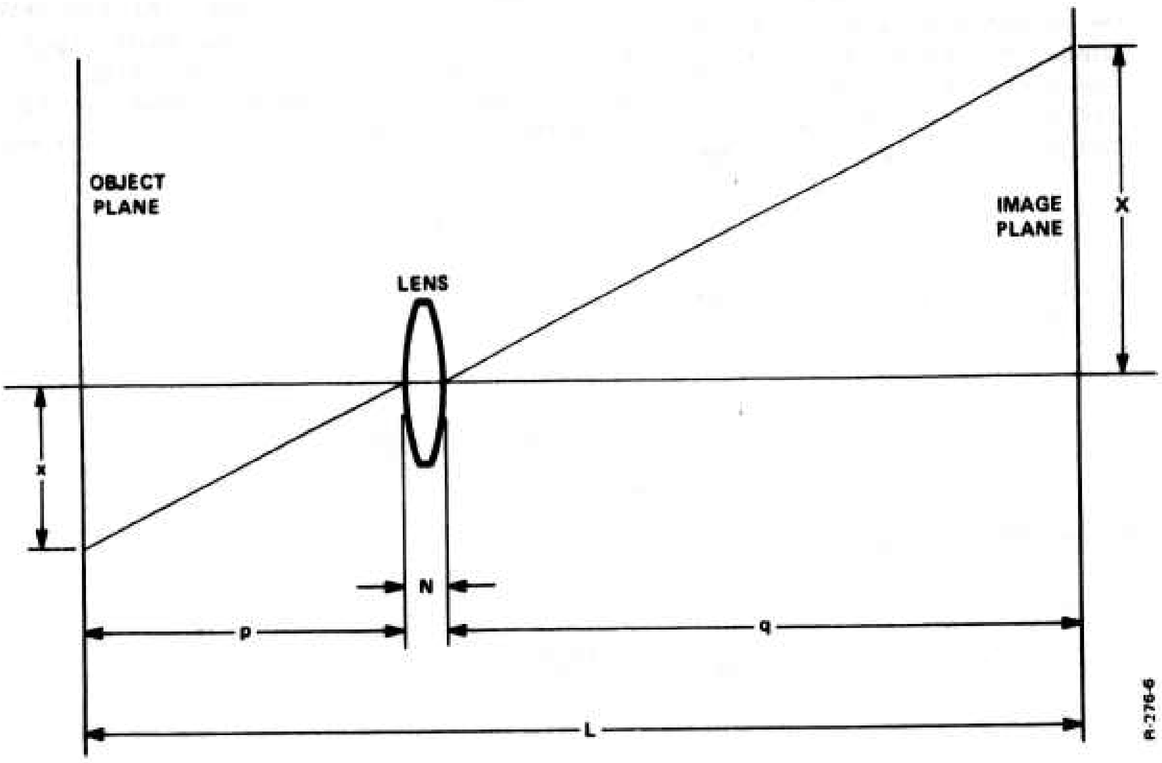

Figure 2-14 - Optical Magnification Geometry

The lens being considered as a replacement, however, is an f/6.3 lens and carriage position accuracy requirements are determined by depth-of-field considerations. (See Section 2.7.2.)

As with the copy platen, uncompensated dynamic errors of the lens and copy carriages would be small (.0002 in.). For the improved servo systems, the dynamic error which cannot be removed by either velocity constant matching or velocity compensation is due primarily to the properties of the tachometer used in the servo system. In the low-speed servo system being recommended for upgrading the EOR, the largest source of tachometer error is ripple. The recommended tachometer has exceptionally low ripple (± 1%) which results in low velocity signal error. For the printing speeds at which the EOR normally runs, it is reasonable to expect that the servo lag can be held to within ± 500 μm. The servo system, under this condition, would be running at a speed such that the tachometer output would be a voltage equivalent to approximately the 500 μm position lag. Any variation in tachometer output voltage would cause an equivalent error in apparent position lag. The ± 1% ripple of the tachometer would, therefore, manifest itself in a ± 5 μm error in position lag. Since the computer under this condition would only compensate for the 500 μm lag, the ± 5 μm would remain as an error in the carriage position during high speed carriage operation. As the speed of the servo is reduced, this uncompensated dynamic error is also reduced, with a lower limit of zero error velocity.

Geometric error in the printed output will also be affected by the geometric fidelity of the lens. It is assumed that the lens error is small compared with other errors.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

This section presents conclusions and recommendations resulting from the various EOR study efforts. The general recommendation is for a disk-based computer control system which performs all the necessary EOR functions, resulting in an EOR system which is completely independent from other systems. The recommended digital servo logic and interface hardware are based on using printed circuit cards which have been developed by Bendix Research Laboratories. Preliminary design details of the recommended EOR system are presented in Appendix C. The following subsections summarize conclusions and recommendations from Section 2.

3.1 CONTROL SYSTEM

Because of its greater flexibility and independence of operation, the independent controller approach is preferred over the tape-driven controller. Savings in hardware cost and savings in initial programming costs for the tape-driven system are fairly small compared with total system cost. Hardware cost differences between the two systems are not great because the computer peripherals comprise a major portion of the cost. Since the peripherals are about the same cost in the two systems, the savings which result from using a smaller control computer in the tape-driven system are small compared with overall costs. Software cost differences are small because the additional programs required for the independent controller system are FORTRAN level programs, which makes them easier to develop than assembly language programs. Part of the cost of the FORTRAN rectification programs required by the independent controller system is in fact partially offset by the need to develop a special magnetic tape reading program for the tape-driven system. This is due to the inevitable incompatability of tape formats between the 1108 and control computer magnetic tape handler system programs.

It is recommended that a disk-based operating system be used rather than a core resident system. The file manipulation capabilities of such systems make programming easier and allow program segments to be overlayed conveniently. Ease of programming reduces costs for both initial programs and subsequent modifications to handle new rectification geometries. Overlaying reduces the amount of core memory required initially and permits easy expansion of program size, which might otherwise be limited by the size of the core memory.

Although the basic disk operated system does not require paper tape or magnetic tape peripherals for operation, some means of backing up the disk is desirable. If another compatible computer system having a magnetic tape unit and a disk unit is available, it can be used to regenerate the program on the disk from magnetic tape. If not, it is recommended that at least one of the EOR systems have a magnetic tape unit. DECtape units (unique to DEC) are somewhat less expensive than 9 track industry standard tape units, but the DECtape is not compatible with other systems and it would take about 5 reels of tape to store the 1.2 M word disk.

Of the three computers studied (DEC PDP 11/35, Modcomp II 25, and Nova 2/10), it is recommended that the DEC PDP 11/35 be selected. It is a very flexible system with well supported software and readily available maintenance. Because the 11/35 can be connected directly to the Bendix servo and parallel I/O hardware, it is also the least expensive computer to interface. A good choice of operating system for the PDP 11/35 is the DOS/BATCH operating system. If a foreground/background capability is desired, the DEC RT-11 system can be used instead.

Benchmark rectification program runs on the PDP 11/35 were executed between 3 and 4 times faster when floating-point instructions were used. The difference is critical because the faster execution times allow simpler programming techniques to be used. It is therefore recommended that the floating-point instruction set option be obtained if the 11/35 is to be used. For the PDP 11/35, the cost of this option is rather modest.

While checking out the benchmark test program, a problem was discovered in the rectification math model given in the EOR users manual. It is, therefore, recommended that the math model be reviewed when programs for the improved EOR system are coded.

Use of one control computer to operate two EOR units is not recommended. Such a system would have lower reliability since the two systems would be dependent on a single controller. Maintenance of one EOR while the other one is in production would also be cumbersome with the dual system. Programs for a dual system would be more complex and would, therefore, cost more to develop. The dual system may also require a faster computer.

3.2 SERVO SYSTEMS

Equipping the EOR carriage and platen drives with digital servo systems requires the replacement of most of the present servo hardware. Replacing the present position-sensing potentiometers with 10,000 counts-per-revolution incremental optical encoders will provide a servo resolution of about 2.5 μm. This is more resolution than is actually required for the EOR but costs no more to attain than the 5 μm resolution considered to be sufficient.

To use presently available servo logic and to achieve good dynamic performance, the response of the EOR carriage and platen servos must be improved. The recommended approach is to use less gear reduction in the copy and lens carriage drive systems and thereby reduce servo drive backlash. The servo drive backlash limits the extent to which forward path gain can be increased to improve servo response. The increased servo response will result in smaller dynamic servo lag errors. This will reduce the uncompensated dynamic error and allow higher slewing velocity without overflowing the digital servo error register. The present AC servo motors should be replaced with new DC torque motor/tachometer assemblies. The new motor/tachometer units will provide longer life (because they run slower) and lower dynamic error due to tachometer ripple. The new motor will also supply the necessary torque to drive the carriages with reduced gearing. Although it is not absolutely essential, the platen motor should also be replaced for improved dynamic error performance and compatability with the new carriage motors. Replacement of the servo motors will require replacement of the servo amplifiers and power supply.

The digital servo logic should employ rate metering or some other form of interpolation to provide smooth servo operation. Development cost for the digital servo logic and servo amplifier electronics can be minimized by using presently available printed circuit card designs. The digital servo designs developed by Bendix Research Laboratories for servo control of photogrammetric instruments can be easily adapted for use in the EOR system. Since this servo logic was designed to work with DEC PDP-11 equipment, servo interface design effort would be minimized by using the PDP 11/35 for the control computer. The additional cost of interfacing with other alternative computers, however, would be small.

The test to determine whether or not the present drum drive system is causing vertical striations in the output film was inconclusive. It is, therefore, not known whether replacing the drum drive will reduce these striations. There are, however, other reasons for replacing the drum drive. If the present fixed speed drum drive is replaced with a servo drive system, exposure can be controlled arbitrarily by controlling drum velocity from the computer. This will allow longer exposure times for use with slow speed, high resolution films. The servo drive system would also be less subject to mechanical wear than the present friction drive system.

The necessary precision for a servo drum drive system can be obtained using an inductosyn type position sensor in conjunction with carrier multiplication electronics. With this equipment a resolution of about 2.5 μm can readily be achieved. A servo design of this type which was developed for the RPIE printer (see Appendix C.5) can be adapted to the EOR.

3.3 OPTICS

With some modifications to the lens turret and copy carriage cable routing it will be possible to cover a magnification range of 0.6X to 6X. It will require a 10-3/4 in. focal length lens. A copy lens with this focal length and an aperture of f/6.3 is available from Rolyn Optics of Arcadia, California. The lens is manufactured by Rank/Wray and has a resolution of 100 to 150 lp/mm. Modifications to the lens turret and copy carriage cable routing are necessary to extend the travel range of these carriages by about 1 in.

Other off-the-shelf copy lenses with larger apertures than the present f/9 are available. Apertures of these lenses range from f/3.5 to f/6.3. Magnification ranges of these lenses do not exactly coincide with those of the present lenses, however, because the focal lengths are not exactly the same.

If new lenses are to be used in the improved EOR system, it will be necessary to determine their exact focal lengths and rear nodal distances. This will require access to a lens bench with a nodal slide. Since the calibration of the carriage positions for best focus and magnification accuracy will be done in the computer of the improved EOR system, a recalibration of the lens and copy carriages will be required. This will involve the determination of lens and copy carriage corrections required to produce correct magnification and focus (or a compromise between them) at several magnification points in the range of each lens. Performance of the new lenses would have to be determined experimentally.

A higher power mercury lamp is available which would increase light source power from 120 W/in. to 200 W/in. The higher power lamp would require a new power supply and would produce more heat in the lamp housing and condenser optics. Because of the higher power requirement and potential problems which could arise from the increased heat, it is not recommended that the higher power lamp be used. It is also not recommended that a xenon lamp be used. The xenon lamp produces considerable infrared radiation which could also damage the condenser optics. With servo control of the drum, improved color reproduction can be attained using filters with the present lamp and longer exposure times (slower drum velocity).

3.4 PERFORMANCE

Performance improvements in the EOR system are expected to be primarily limited to the areas of reliability and maintainability. Replacing the analog servo systems with digital servo systems will increase reliability and eliminate the present analog interface circuitry which is sensitive and requires periodic adjustment. The new servo components will also provide longer life because they run at lower speed. Replacing the present tape reader and decoder electronics with a digital control computer will eliminate problems arising from paper tape errors and imperfections. The independent controller system approach will provide a great reduction in job turn-around time since the 1108 and 1401 are eliminated from the loop.

The basic mechanical components which primarily determine geometric accuracy and also effect resolution would not be changed in the improved system. It is, therefore, expected that there will be no increase in geometric fidelity or resolution. It is possible that the new lens will improve resolution, but no tests were made to determine this. Resolution attainable with new lenses in the EOR should be determined by testing them in the EOR system. Typical production resolution obtained with the present lenses is well below what they are capable of achieving under ideal conditions. Unless the new lens has some property such as flatter field, which would allow better resolution over a wider field, significant improvements in resolution are not anticipated. The new lens, if used at full aperture, will have a smaller depth of field and resolution will, therefore, be more sensitive to lens and copy carriage position errors. Analysis shows that slit width can have a significant effect on resolution when there is a large difference between optical and scan magnification. These factors limit what can be obtained with the EOR optical and mechanical hardware.

The improved EOR servos will have better dynamic response than the present servos. It is expected that a velocity constant of 10 per second or greater can be achieved with the reduced servo backlash. This alone will reduce uncompensated dynamic servo errors. In addition, the improved tachometers will further reduce this error. Servo resolution will be increased from 4096 counts per inch to 10,000 counts per inch. In the improved system, each count will produce 2.54 μm of carriage or platen travel.

In the present EOR, servo commands are calculated for each 0.01 in. or 250 μm increment of output drum travel. In the improved EOR system (independent controller approach) rectification calculations can be performed with closer spacing. For example, with the present drum velocity of about 1.25 mm/sec, carriage and platen positions can be calculated at 12.5 μm spacing. For the present relatively slow print velocity, this is not a particularly significant advantage, but could be important if it ever becomes desirable to increase printing speed.

APPENDIX A

IMAGE MOTION SMEAR TRANSFER FUNCTION

If an image function f(u,v) is moved a distance d during exposure of the recording film, the image recorded on the film will be smeared in the direction of motion. For this derivation, it is assumed that the image moves at a constant rate and in a straight line during exposure. For convenience, it is also assumed that the motion is along the v axis. The image function g(u,v) which would be recorded on the output film (normalized for smear distance) can be expressed by

$$g(u,v) = \frac{1}{d}\int_{-\frac{d}{2}}^{\frac{d}{2}} F(u,\ v-s)ds$$

where d is the smear distance and s is a parameter which moves the image along the smear line. Taking the Fourier transform and reversing the order of integration gives the frequency domain output function $G(\sigma,\omega)$:

$$G(\sigma,\omega) = F(\sigma,\omega)\ \frac{1}{d}\int_{-\frac{d}{2}}^{\frac{d}{2}} e^{-j\omega s}\ ds$$

Carrying out the integration gives

$$G(\sigma,\omega) = F(\sigma,\omega)\ \frac{2}{\omega d}\ \frac{e^{\frac{j\omega d}{2}} - e^{\frac{-j\omega d}{2}}}{2j}$$

which can be expressed in the form

$$G(\sigma,\omega) = F(\sigma,\omega)\ \frac{\sin\left(\frac{\omega d}{2}\right)}{\left(\frac{\omega d}{2}\right)}$$

Now if a modulation transfer function (MTF) is defined as the ratio of the output frequency function divided by the input frequency function, this MTF is given by:

$$\mathrm{MTF} = \frac{G(\sigma,\omega)}{F(\sigma,\omega)} = \frac{\sin\left(\frac{\omega d}{2}\right)}{\left(\frac{\omega d}{2}\right)}$$

This MTF describes how spatial frequency components of an arbitrary input image function are affected by uniform linear image motion during exposure. The degradation occurs only in the direction of image motion (v) since the MTF is independent of the σ (corresponding to u in the spatial domain).

APPENDIX B

BENCHMARK PROGRAM LISTINGS

```
BENCH2,KB:<BENCH2/ON

FORTRAN V06.13                      01:04:14    08-OCT-75    PAGE    1

      C       BENCHMARK 2--REPETITIVE FRAME CALCULATIONS
      C       WITH BIGVK PRIMARILY LESS THAN OR EQUAL TO 0
      C       INITIAL VALUES--
              TINYVO=.1
              S=1.
              T=0.
              H=1.0
              F=6.
              R=3439.
              DELTAV=.0005
              FK=13.9763779
              RN=.0984252
      C       INITIAL CALCULATIONS--
              T=T/57.29578
              SINT=SIN(T)
              COST=COS(T)
              TANT=SINT/COST
              SF=S*F
              ALPHA=T+ATAN2(TINYVO,F)
              SINTH=SIN(ALPHA)*(R+H)/R
              THETA=ATAN2(ABS(SINTH),SQRT(1.-SINTH**2))
              R=(R*SF)/H
              BETA=THETA-ALPHA-(DELTAV/(2.*R))
              BIGVK=R*SIN(BETA)
              WRITE(6,1000) BIGVK
        1000  FORMAT(' VO=',F9.1/)
              SF=BIGVK/(SIN(ALPHA)/COS(ALPHA))
              PAUSE
      C       ITERATIVE CALCULATIONS--
              DO 40 I=1,10000
              BETA=BETA-DELTAV/R
              BIGVK=BIGVK-COS(BETA)*DELTAV
              SF=SF-SIN(BETA)*DELTAV
              IF (BIGVK) 20,20,10
          10  TINYVK=F*(BIGVK-SF*TANT)/(SF+BIGVK*TANT)
              GO TO 30
          20  ANGLE=T+ABS(ATAN2(BIGVK,SF))
              TINYVK=(-SIN(ANGLE)/COS(ANGLE))*F
          30  RM=SF/(F*COST-TINYVK*SINT)
              BK=FK*(RM+1.)
              LK=BK*(1.+1./RM)+RN
          40  CONTINUE
              PAUSE
              WRITE(6,1010) BIGVK
        1010  FORMAT(' VF=',F4.1/)
              END

        ROUTINES CALLED:
        SIN    , COS    , ATAN2 , ABS    , SQRT

        OPTIONS =/ON,/OP:1

        BLOCK      LENGTH
        MAIN.   598    (002254)*

FORTRAN V06.13                      01:04:14    08-OCT-75    PAGE    2

        **COMPILER ----- CORE**
```

```
BENCH1,KB:<BENCH1/ON

FORTRAN V06.13                          00:25:25    05-DEC-75    PAGE     1

      C     BENCHMARK 1--REPETITIVE FRAME CALCULATIONS
      C     INITIAL VALUES--
            TINYVO=1.37
            S=1.
            T=45.
            H=100.
            F=6.
            R=3439.
            DELTAV=.0005
            FK=13.9763779
            RN=.0984252
      C     INITIAL CALCULATIONS--
            T=T/57.29578
            SINT=SIN(T)
            COST=COS(T)
            TANT=SINT/COST
            SF=S*F
            ALPHA=T+ATAN2(TINYVO,F)
            SINTH=SIN(ALPHA)*(R+H)/R
            THETA=ATAN2(ABS(SINTH),SQRT(1.-SINTH**2))
            R=(R*SF)/H
            BETA=THETA-ALPHA-(DELTAV/(2.*R))
            BIGVK=R*SIN(BETA)
            WRITE(6,1000) BIGVK
       1000 FORMAT(' V0=',F4.1/)
            SF=BIGVK/(SIN(ALPHA)/COS(ALPHA))
            PAUSE
      C     ITERATIVE CALCULATIONS--
            DO 40 I=1,10000
            BETA=BETA-DELTAV/R
            BIGVK=BIGVK-COS(BETA)*DELTAV
            SF=SF-SIN(BETA)*DELTAV
            IF (BIGVK) 20,20,10
         10 TINYVK=F*(BIGVK-SF*TANT)/(SF+BIGVK*TANT)
            GO TO 30
         20 ANGLE=T+ABS(ATAN2(BIGVK,SF))
            TINYVK=(-SIN(ANGLE)/COS(ANGLE))*F
         30 RM=SF/(F*COST-TINYVK*SINT)
            BK=FK*(RM+1.)
            LK=BK*(1.+1./RM)+RN
         40 CONTINUE
            PAUSE
            WRITE(6,1010) BIGVK
       1010 FORMAT(' VF=',F4.1/)
            END

      ROUTINES CALLED:
      SIN   , COS    , ATAN2 , ABS   , SQRT

      OPTIONS =/ON,/OP:1

      BLOCK      LENGTH
      MAIN.   600    (002260)*

FORTRAN V06.13                          00:25:25    05-DEC-75    PAGE     2


      **COMPILER ----- CORE**
         PHASE       USED   FREE
```

```
        DECLARATIVES 00622 10186
        EXECUTABLES  01023 09785
        ASSEMBLY     01323 14125

$^C
.KI

$RU LINK

LINK V01-04
#BENCH1<BENCH1,FTNLIB/L/E


SPACE USED 012264, SPACE FREE 057346
#^C
.KI

$RU BENCH1

VO= 9.9

A005 000000
$CO

A005 000000
$CO

VF= 4.9

$
```

```
          PHASE        USED  FREE
        DECLARATIVES 00622 10186
        EXECUTABLES  01023 09785
        ASSEMBLY     01319 14129

$^C
.KI

$RU LINK

LINK V01-04
#BENCH2<BENCH2,FTNLIB/L/E


SPACE USED 012264, SPACE FREE 057346
#^C
.KI

$RU BENCH2

VO=       0.1

A005 000000
$CO

A005 000000
$CO

VF=-4.9

$
```

```
BENCH3,KB:<BENCH3/ON

FORTRAN V06.13                    00:58:30     08-OCT-75    PAGE     1

C      BENCHMARK 3--REPETITIVE FRAME CALCULATIONS
C      TO SEE WHY INITIAL CALCULATIONS BLOWUP WHEN
C      TINYVO IS LESS THAN OR EQUAL TO 0
C      INITIAL VALUES--
       TINYVO=-1.
       S=1.
       T=0.
       H=1.0
       F=6.
       R=3439.
       DELTAV=.0005
       FK=13.9763779
       RN=.0984252
C      INITIAL CALCULATIONS--
       T=T/57.29578
       SINT=SIN(T)
       COST=COS(T)
       TANT=SINT/COST
       SF=S*F
       ALPHA=T+ATAN2(TINYVO,F)
       ANGLE=ALPHA*57.29578
       WRITE(6,1020) ANGLE
 1020  FORMAT(' ALPHA=',F9.4)
       SINTH=SIN(ALPHA)*(R+H)/R
       THETA=ATAN2(ABS(SINTH),SQRT(1.-SINTH**2))
       ANGLE=THETA*57.29578
       WRITE(6,1030) ANGLE
 1030  FORMAT(' THETA=',F9.4)
       R=(R*SF)/H
       BETA=THETA-ALPHA-(DELTAV/(2.*R))
       ANGLE=BETA*57.29578
       WRITE(6,1040) ANGLE
 1040  FORMAT(' BETA=',F9.4)
       BIGVK=R*SIN(BETA)
       WRITE(6,1000) BIGVK
 1000  FORMAT(' VO=',F9.1/)
       SF=BIGVK/(SIN(ALPHA)/COS(ALPHA))
       PAUSE
C      ITERATIVE CALCULATIONS--
       DO 40 I=1,10000
       BETA=BETA-DELTAV/R
       BIGVK=BIGVK-COS(BETA)*DELTAV
       SF=SF-SIN(BETA)*DELTAV
       IF (BIGVK) 20,20,10
   10  TINYVK=F*(BIGVK-SF*TANT)/(SF+BIGVK*TANT)
       GO TO 30
   20  ANGLE=T+ABS(ATAN2(BIGVK,SF))
       TINYVK=(-SIN(ANGLE)/COS(ANGLE))*F
   30  RM=SF/(F*COST-TINYVK*SINT)
       BK=FK*(RM+1.)
       LK=BK*(1.+1./RM)+RN
   40  CONTINUE
       PAUSE
       WRITE(6,1010) BIGVK
 1010  FORMAT(' VF=',F4.1/)

FORTRAN V06.13                    00:58:30     08-OCT-75    PAGE     2

       END
```

```
ROUTINES CALLED:
SIN    , COS    , ATAN2 , ABS    , SQRT

OPTIONS =/ON,/OP:1

BLOCK        LENGTH
MAIN.    702     (002574)*

**COMPILER ----- CORE**
   PHASE        USED  FREE
DECLARATIVES 00622 10186
EXECUTABLES  01023 09785
ASSEMBLY     01363 14085

#^C
.KI

$RU LINK

LINK V01-04
#BENCH3<BENCH3,FTNLIB/L/E


SPACE USED 012264, SPACE FREE 057346
#^C
.KI

$RU BENCH3

ALPHA=  -9.4623
THETA=   9.4651
BETA=  18.9274
VO=   6693.1

A005 000000
$
```

```
BENCH4,KB:<BENCH4/ON
FORTRAN V06.13                              02:44:41     08-OCT-75    PAGE     1
C           BENCHMARK 4--REPETITIVE FRAME CALCULATIONS
C           SYMMETRIC TO BENCHMARK 2
C           INITIAL VALUES--
            TINYVO=4.9
            S=1.
            T=0.
            H=1.0
            F=6.
            R=3439.
            DELTAV=.0005
            FK=13.9763779
            RN=.0984252
C           INITIAL CALCULATIONS--
            T=T/57.29578
            SINT=SIN(T)
            COST=COS(T)
            TANT=SINT/COST
            SF=S*F
            ALPHA=T+ATAN2(TINYVO,F)
            SINTH=SIN(ALPHA)*(R+H)/R
            THETA=ATAN2(ABS(SINTH),SQRT(1.-SINTH**2))
            R=(R*SF)/H
            BETA=THETA-ALPHA-(DELTAV/(2.*R))
            BIGVK=R*SIN(BETA)
            WRITE(6,1000) BIGVK
      1000  FORMAT(' VO=',F9.1/)
            SF=BIGVK/(SIN(ALPHA)/COS(ALPHA))
            PAUSE
C           ITERATIVE CALCULATIONS--
            DO 40 I=1,10000
            BETA=BETA-DELTAV/R
            BIGVK=BIGVK-COS(BETA)*DELTAV
            SF=SF-SIN(BETA)*DELTAV
            IF (BIGVK) 20,20,10
        10  TINYVK=F*(BIGVK-SF*TANT)/(SF+BIGVK*TANT)
            GO TO 30
        20  ANGLE=T+ABS(ATAN2(BIGVK,SF))
            TINYVK=(-SIN(ANGLE)/COS(ANGLE))*F
        30  RM=SF/(F*COST-TINYVK*SINT)
            BK=FK*(RM+1.)
            LK=BK*(1.+1./RM)+RN
        40  CONTINUE
            PAUSE
            WRITE(6,1010) BIGVK
      1010  FORMAT(' VF=',F4.1/)
            END

      ROUTINES CALLED:
      SIN   , COS    , ATAN2 , ABS    , SQRT

      OPTIONS =/ON,/OP:1

      BLOCK       LENGTH
      MAIN.   598     (002254)*
```

```
FORTRAN V06.13                              02:44:41     08-OCT-75    PAGE     2

      **COMPILER ----- CORE**
```

```
           PHASE        USED  FREE
     DECLARATIVES 00622 10186
     EXECUTABLES  01023 09785
     ASSEMBLY     01319 14129

#^C
.KI

$RU LINK

LINK V01-04
#BENCH4<BENCH4,FTNLIB/L/E


SPACE USED 012264, SPACE FREE 057346
#^C
.KI

$RU BENCH4

V0=     4.9

A005 000000
$CO

A005 000000
$CO

VF=-0.1

$
```

```
BENCH5,KB:<BENCH5/ON

FORTRAN V06.13                    00:02:22     09-DEC-75    PAGE     1

      C        BENCHMARK 5--REPETITIVE FRAME CALCULATIONS
      C        HALF OF BENCHMARK 2 AND HALF OF BENCHMARK 4
      C        INITIAL VALUES--
               TINYVO=2.5
               S=1.
               T=0.
               H=1.0
               F=6.
               R=3439.
               DELTAV=.0005
               FK=13.9763779
               RN=.0984252
      C        INITIAL CALCULATIONS--
               T=T/57.29578
               SINT=SIN(T)
               COST=COS(T)
               TANT=SINT/COST
               SF=S*F
               ALPHA=T+ATAN2(TINYVO,F)
               SINTH=SIN(ALPHA)*(R+H)/R
               THETA=ATAN2(ABS(SINTH),SQRT(1.-SINTH**2))
               R=(R*SF)/H
               BETA=THETA-ALPHA-(DELTAV/(2.*R))
               BIGVK=R*SIN(BETA)
               WRITE(6,1000) BIGVK
        1000   FORMAT(' VO=',F9.1/)
               SF=BIGVK/(SIN(ALPHA)/COS(ALPHA))
               PAUSE
      C        ITERATIVE CALCULATIONS--
               DO 40 I=1,10000
               BETA=BETA-DELTAV/R
               BIGVK=BIGVK-COS(BETA)*DELTAV
               SF=SF-SIN(BETA)*DELTAV
               IF (BIGVK) 20,20,10
          10   TINYVK=F*(BIGVK-SF*TANT)/(SF+BIGVK*TANT)
               GO TO 30
          20   ANGLE=T+ABS(ATAN2(BIGVK,SF))
               TINYVK=(-SIN(ANGLE)/COS(ANGLE))*F
          30   RM=SF/(F*COST-TINYVK*SINT)
               BK=FK*(RM+1.)
               LK=BK*(1.+1./RM)+RN
          40   CONTINUE
               PAUSE
               WRITE(6,1010) BIGVK
        1010   FORMAT(' VF=',F4.1/)
               END

          ROUTINES CALLED:
          SIN    , COS    , ATAN2 , ABS    , SQRT

          OPTIONS =/ON,/OP:1

          BLOCK      LENGTH
          MAIN.   598    (002254)*

FORTRAN V06.13                    00:02:22     09-DEC-75    PAGE     2


          **COMPILER ----- CORE**
             PHASE        USED  FREE
```

```
                    DECLARATIVES 00622 10186
                    EXECUTABLES  01023 09785
                    ASSEMBLY     01319 14129

#^C
.KI

$RU LINK

LINK V01-04
#BENCH5<BENCH5,FTNLIB/L/E


SPACE USED 012264, SPACE FREE 057346
#^C
.KI

$RU BENCH5

VO=       2.5

A005 000000
$CO

A005 000000
$CO

VF=-2.5

 $
```

APPENDIX C

IMPROVED EOR SYSTEM

This appendix presents a description of the improved EOR system which was recommended as a result of the study. This system is an implementation of the independent controller concept discussed in Section 2.1. Unlike the present EOR system which relies on the 1108 for rectification computations and the 1401 for tape conversion, the improved system operates completely independently. The control computer of the improved system generates model motion, computes the rectification relationships, and controls servo motion in real time.

The system description presented in this appendix concentrates on those components which have been defined as a result of this study. Therefore, in addition to the descriptions of the overall system and operating procedures, detailed descriptions of computer programs, the interface, and servo systems are presented.

C.1 SYSTEM DESCRIPTION

A diagram of the improved EOR system is shown in Figure C-1. The major components of the system are the present optical-mechanical subsystem (with improved servos) and the control computer. The optical-mechanical subsystem includes the copy carriage, lens carriage, copy platen, print drum, lamp housing, condenser optics, and miscellaneous power supplies housed in the large cabinet of the present EOR system. These components are functionally unchanged in the improved system; however, new servos to drive the carriages and drum have been added.

Although a DEC PDP 11/35 computer is recommended, no specific computer is indicated in the diagram since any of the three computers considered in Section 2.2 could be used. Standard peripherals attached to the computer include a 1.2 M word cartridge disk system, a CRT terminal, and a TTY terminal. All the programs for the improved EOR system are stored on a removable cartridge disk. During system startup, the computer system operating programs are loaded into the computer. The operating programs then load the various EOR programs from the disk as needed during operation of the EOR system. The disk is also used for storing data generated during certain modes of system operation.

The CRT terminal is the primary interface device between the EOR system and the operator. It consists of a CRT display system and a keyboard. Through the keyboard, the operator enters data and commands to the EOR programs. The programs display certain variables in real time and convey messages to the operator through the CRT display. To facilitate the real time display function, the terminal is equipped with an addressable cursor feature. This allows the cursor to be moved rapidly back and forth between the real time display area of the screen and the message area.

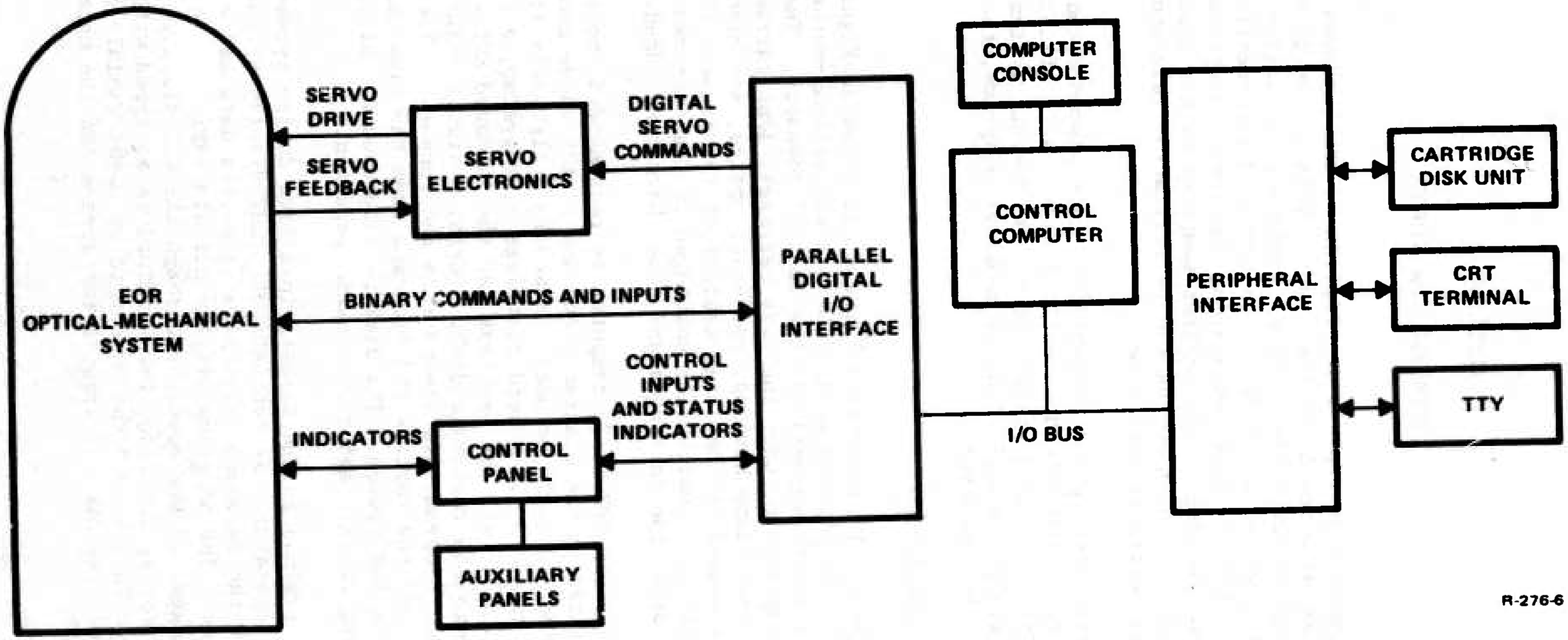

Figure C-1 - Improved EOR System

The TTY terminal is used primarily for hard copy output of data such as rectification parameters or calibration data.

A parallel digital I/O interface conveys information in digital form between the computer and various components of the EOR system. This interface consists of a combination of parallel digital I/O equipment available from the computer manufacturer and equipment available from and/or developed by Bendix Research Laboratories. Data is transmitted through this interface as 16-bit words transferred in parallel between the computer and one of several 16-bit channels. Five of these channels are output channels and two are input channels. The interface equipment is described in more detail in Appendix C.4

Four of the output channels are used to convey digital servo output increments from the computer to the servo electronics. Servo increments are transmitted as 12-bit parallel words from the interface to the servo logic. The servo electronics for each servo system converts differences between commanded and actual incremental servo positions to voltages which drive the servo motors. Servo feedback to the servo electronics includes both digital position feedback and tachometer feedback. The servo systems for the EOR carriages and print drum are described in Appendix C.5.

Other digital information passed between the EOR hardware and the computer consists of certain binary commands from the computer and binary inputs to the computer. Binary commands from the computer include the shutter control and certain indicator lamps. Binary inputs to the computer from the EOR unit include signals from limit switches on the carriages and drum, zero pulse signals from the carriage quantizers, the lens selection indicator switch signal, and a shutter status signal.

To provide certain operator interaction functions which would be difficult to implement with the CRT terminal, the improved EOR system is equipped with a control panel. This panel contains switches to start and stop rectification and to cause the program to be interrupted.

It contains lamps to display certain conditions such as whether or not a rectification run is in progress, an error has occurred, the shutter is open, a lamp failure has occurred, or a fan failure has occurred. The panel also contains an incremental input control for entering data into the computer at a variable rate. This control is normally used for manually positioning the servos during setup or maintenance procedures.

In addition to the main control panel, there are two auxiliary control panels on which certain functions of the main control panel are duplicated. One auxiliary panel is the X and Y Copy Platen Control Panel of the present EOR system. On this panel, the normal X axis adjustment potentiometer is replaced with an incremental input control. This allows control of the copy platen servo through the computer programs during setup. The other auxiliary panel is a service panel containing an incremental input control and several switches. This panel is on a portable control box which can be hand-carried by the serviceman. This control box facilitates the carriage calibration maintenance function by allowing the operator to manually position the carriages and platen while observing mechanical readings on the Ames gauge The switches permit communication with the calibration programs to facilitate stepping through the calibration procedure without having to return to the main control panel.

System operating modes of the improved EOR system include the rectification mode, the calibration mode, and the diagnostic mode. These operating modes are determined by the computer programs. The rectification mode is the basic operating mode of the system. This mode implements the necessary system control functions for setting up the system in preparation for printing, and actual printing. Rectification parameters can be entered using the CRT terminal, and the platen and other servos can be positioned manually to facilitate aligning the photograph on the platen. In the rectification mode, START and STOP pushbuttons on the control panel control the starting and stopping of the rectification printing process. A trial rectification submode can be made available which allows the entire rectification run to be computed at a speed greater than normal real time speed, with control outputs disconnected. Rectification calculations can then be checked before actual printing to determine if any calculations exceed the limits of the rectifier hardware.

The calibration mode is provided to facilitate the calibration of the platen, lens carriage, and copy carriage. In this mode, control panel pushbutton functions are changed, allowing the operator to step from one calibration point to the next and store measured corrections. Corrections are measured by moving the carriage or platen with the incremental input until the mechanical position indicator reads correctly at the commanded position. The correction is then stored by depressing one of the panel pushbuttons.

The diagnostic mode provides a means of checking the parallel digital I/O interface and the servos. In this mode the servos can be operated manually to test them for proper operation. Parallel binary outputs can be checked by setting bit patterns in the computer console switches and observing outputs on an oscilloscope. Parallel binary inputs can be checked by applying signals from external sensors (such as limit switches) and observing the resulting bit patterns which are displayed on the CRT terminal. The diagnostic mode does not test the computer and standard peripherals. Programs for testing these components are supplied by the computer manufacturer and are delivered with the system.

During rectification printing, the EOR system is automatically controlled by the computer acting on instructions of the rectification mode programs. The rectification mode programs compute the proper drum, platen, copy carriage, and lens carriage positions so that imagery from the input photo is printed on the output film in a manner which achieves the desired rectification. (For EOR theory of operation see Lavine, S.W., "A Slit-Scan Electro-Optical Rectifier", Photogrammetric Engineering, December 1961.) The rectification mode programs which determine this process allow several alternate rectification geometries to be used. The basic alternatives include oblique frame, panoramic, and linear rectification, but provision is made in the programs to expand the list of alternatives.

A signal flow diagram of the rectification mode programs is shown in Figure C-2. After the rectification calculations and servo positions have been initialized, the iterative rectification calculations are driven by a velocity signal ΔV which is generated by the programs. The velocity signal is integrated and scaled to obtain print drum position. The velocity signal is also applied to the earth curvature correction calculation to obtain model space coordinates Sf and Vk. The rectification geometry transformation operates on Sf and Vk to produce platen position vk and optical magnification M. Platen position vk is corrected for position errors with a calibration data table to obtain the corrected platen position to be applied to the servos. Magnification M is applied to the autofocus calculations to obtain copy carriage position Lk and lens carriage position Bk. These carriage positions are also corrected for position errors to obtain corrected outputs. A possible path exists between the rectification geometry calculation block and the velocity generation block, shown as dotted line in Figure C-2. This indicates the possibility of varying print velocity as a function of rectification geometry variables to achieve a more uniform exposure of the output film. Although it may not be necessary to do so, light level variations due to optical magnification variations and non-uniform input film characteristics could be compensated.

There are some additional program functions (not shown in Figure C-2) which operate on the servo outputs before they are transmitted to the hardware. To control servo positions under dynamic conditions, a velocity compensation is applied to the servo outputs. This compensates for dynamic servo errors. The servo outputs are also velocity and acceleration limited to prevent servo commands from exceeding servo hardware performance limits. Finally, since the servo hardware is incremental in nature, successive servo output positions are differenced to obtain the position increments which are actually transmitted to the servos. A more detailed explanation of this is presented in Appendix C.5.

C.2 SAMPLE OPERATING PROCEDURES

The computer programs for the new EOR system were designed with emphasis on operating ease and flexibility. The programs require a definite response from the operator only in two instances - when the operating mode (rectification, calibration, or diagnostic) must be selected and when the rectification option in rectification mode must be chosen. Otherwise, the programs do not lead the operator step-by-step through the functions that need to be performed. The operations available to the operator are listed for his information. He orders the operations himself by telling the program what to do next.

At any time after the programs are loaded and before they are ended, the operator can display data items. He does so by typing the data item's mnemonic and an action character. The operator also can change the values of

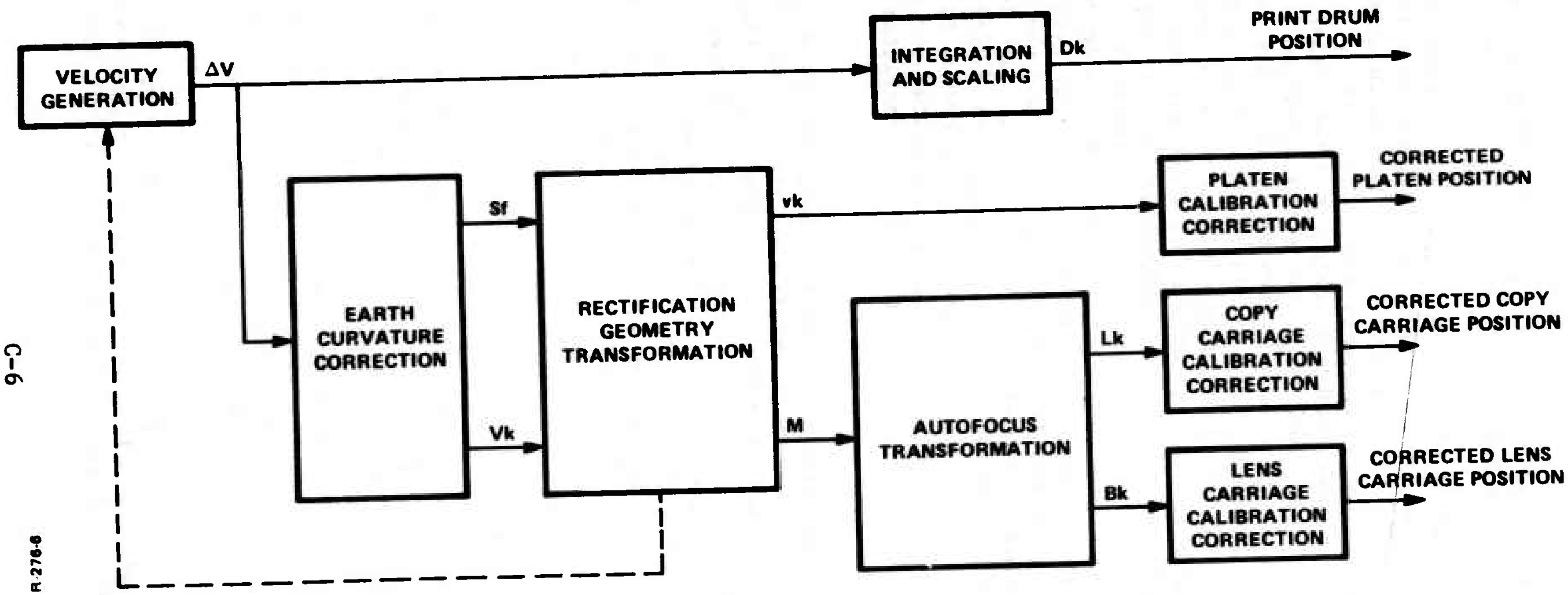

Figure C-2 - Signal Flow Diagram of Rectification Mode Programs data items whenever he chooses except during printing. To change a data item's value the operator types its mnemonic, an equal sign, and the new value. As examples, all possible typed entries for a data item called TIME are listed in the following table.

Typed Entry	Program's Response
TIME?	The program determines the value stored in memory for the data item and prints it as TIME=0.0
TIME=3	The program changes to 3.0 the value stored in memory for the data item, TIME.
TIME/	The program continuously displays the value of TIME at the top of the CRT screen.
TIME\	The program stops continuously displaying the value of TIME.

Presumably, the operator has a list of all of the mnemonics available to him along with explanations of how the data items are used by the program.

The following sequence is not a set of general operating procedures. It is a sample to illustrate how the operator might run the new EOR system in a given situation. The situation assumed is that the operator is rectifying an oblique frame copy negative. Actions taken by the operator (O) and the computer programs (P) are noted.

Step 1: System Startup

O: (1) Turns on the computer and rectifier.

(2) Insures that the CRT terminal has power on.

(3) Loads the EOR disk cartridge.

(4) Boots the system monitor into memory from disk.

Step 2: Program Loading

O: (1) Initializes the monitor.

(2) Types

RUN EOR

to load the EOR programs from disk into memory.

Step 3: Mode Selection

P: (1) Moves the servos to their reference positions.

(2) Prints

R=RECTIFICATION MODE
C=CALIBRATION MODE
D=DIAGNOSTIC MODE
E=END PROGRAM
SELECT ONE

O: (1) Types

R

to select rectification mode.

Step 4: Option Selection

P: (1) Prints

01=LINEAR ENLARGEMENT
02=FRAME
03=STRIP
04=PANORAMIC
:
93=STRIP II
ER=END RECTIFICATION MODE
SELECT ONE

O: (1) Types

02

to select the frame option.

Step 5: Rectification Setup

P: (1) Prints

THE FOLLOWING COMMANDS ARE AVAILABLE (WHEN PRINTING IS NOT IN PROCESS) UNTIL NO OR ER IS TYPED:

IN=INITIALIZE RECTIFICATION PARAMETERS

PP=DEFINE PRINCIPAL POINT OR COPY AT CURRENT CARRIAGE POSITION

AS=MOVE ALL SERVOS TO INITIAL POSITIONS

ND=MOVE ALL SERVOS BUT DRUM TO INITIAL POSITIONS

NO=ALLOW SELECTION OF A NEW RECTIFICATION OPTION

ER=END RECTIFICATICN MODE

O: (1) Inputs values of data items required by the frame option by typing

VO=1.37

VF=-5.0

S=1.0

T=45.0

:

(2) Types

IN

to initialize rectification parameters and determine the correct lens.

P: (1) Computes initial rectification parameters.

(2) Prints

LENS SELECTION IS 7" LENS

O: (1) Loads copy negative into the rectifier copy platen.

(2) Sets the 7 in. lens into position.

(3) Types

RATE=P

to cause incremental rate inputs to be applied to the copy platen.

(4) Uses incremental rate inputs to align the principal point of the copy negative with the coordinate system of the rectifier.

(5) Types

PP

to define the principal point of the copy for the program.

(6) Loads film onto the recording drum.

(7) Types

AS

to slew all servos to their starting positions as determined during initialization.

Step 6: Continuous Display Setup

O: (1) Types

TIME/

SCANS/

LK/

to continuously display elapsed time, number of scans completed, and lens carriage position.

P: (1) Continuously prints

TIME=X.XX SCANS=XX LK=XX.XXX

at the top of the CRT screen.

Step 7: Rectification

O: (1) Pushes the START button.

P: (1) Starts rectifying the copy and printing the rectified image.

(2) Turns on the STOP button when rectification is finished.

O: (1) Removes the copy negative from the rectifier copy platen.

(2) Removes the print from the recording drum.

The operator might now go back to Step 5 to set up another frame copy to be rectified, type "NO" to return to Step 4 and select a new rectification option, or continue on with Step 8. (At any time during rectification the operator could have halted printing by pushing the STOP button. All of the setup functions then would have been available to him. To continue rectifying he would have had to push the START button once again.

Step 8: Mode Exiting

O: (1) Types

ER

to exit rectification mode.

Step 9: Program Ending

P: (1) Prints (see Step 3)

R=RECTIFICATION MODE

C=CALIBRATION MODE

D=DIAGNOSTIC MODE

E=END PROGRAM

SELECT ONE

O: (1) Types

E

to end the program. (The operator could have gone to calibration mode or diagnostic mode instead.)

P: (1) Moves the servos to their reference positions.

(2) Stops continuous display.

(3) Returns to the monitor.

Step 10: System Shutdown

O: (1) Unloads the EOR disk cartridge.

(2) Turns off the computer and rectifier.

C.3 COMPUTER PROGRAMS

The new EOR programs must provide for data acquisition, analysis, and control in real time. Consequently, much of the coding will be done in the assembly language of the system's computer. Where time is not critical, however, FORTRAN will be used. Programs written in FORTRAN have the advantage of being more easily understood and changed.

As envisioned, the EOR programs consist of several distinct program sections each of which performs its own unique set of functions. To ease memory size requirements, not all program sections exist in core memory simultaneously. Only three sections remain in memory continuously while the EOR programs are running. They are the clock program, the CRT driver, and the loader. Each of these sections performs functions which are required by, and common to, all of the remaining program sections. The functions executed by the remaining sections are needed only under special conditions, fall into natural divisions, and are mutually exclusive. Therefore, each of these sections is stored on disk as an overlay and is read into memory during system operation only as it is needed. All of the overlays occupy the same area of core memory. Figure C-3 is a map indicating the overlay structure and the locations of the various program sections in memory when they are loaded. Note that the overlay configuration is expanded in the case of the rectification mode overlay to include suboverlays which correspond to the rectification options.

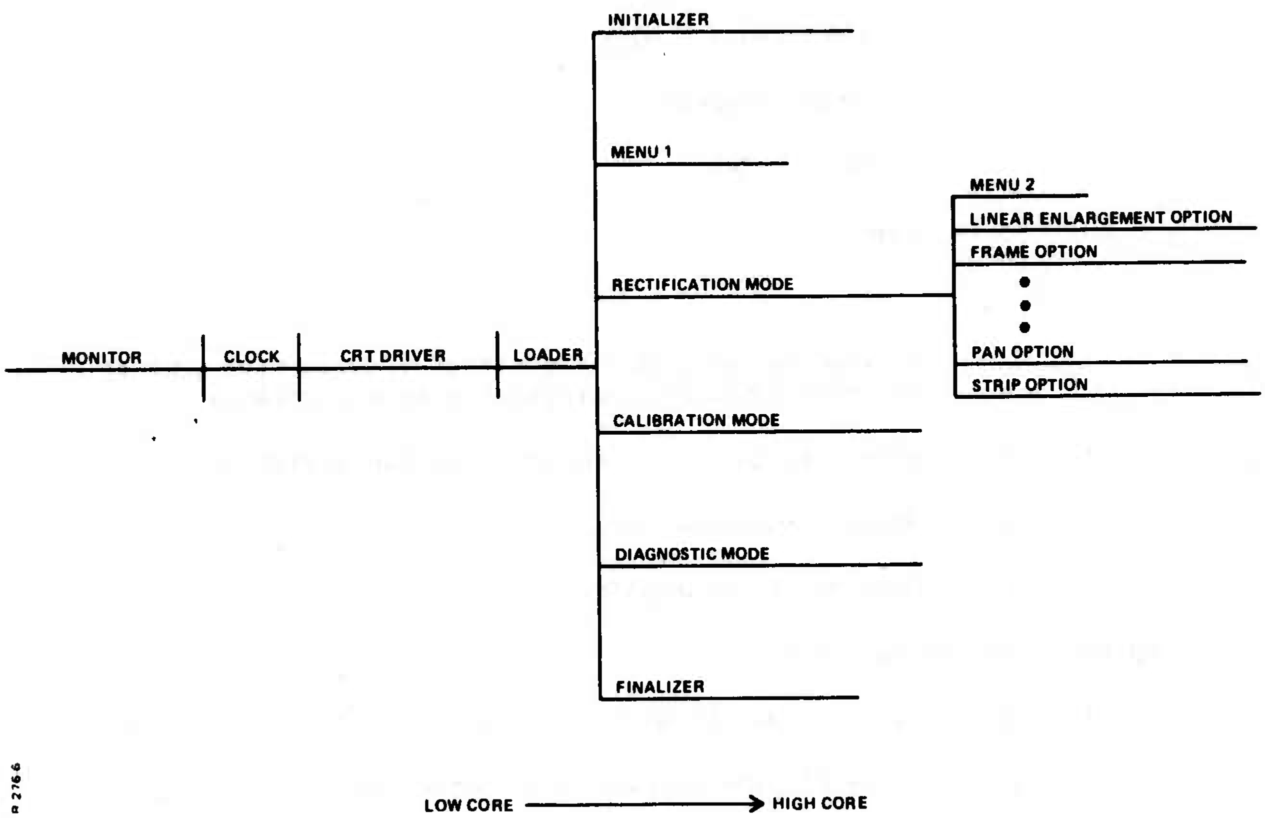

Figure C-3 - Memory Map

The monitor resides in memory during system operation for three reasons. First, FORTRAN uses monitor routines. Second, the EOR programs access the disk by using monitor I/O calls. Third, the monitor takes care of handling unusual situations such as power going down.

C.3.1 Program Loading

When the operator of the EOR system is ready to run the programs he types a command to the monitor. In response, the monitor reads the clock program, CRT driver, loader, and initializer into core memory from the disk. Control is transferred to the initializer when program loading is finished.

C.3.2 Initializer

The purpose of the initializer is to prepare the system for operation. Figure C-4 is a flowchart of the initializer. Most importantly, it performs the following functions:

(1) Reads from a disk file the calibrated corrections for the copy platen, copy carriage, and lens carriage. These corrections are computed and stored on disk during the calibration mode overlay.

(2) Causes clock interrupts to begin at the desired frequency.

(3) Moves each of the four rectifier servos to its reference position. The initializer, not knowing the current servo positions, identifies the reference point of a servo by slowly running the servo into its limit and then backing up to a quantizer zero pulse position. Absolute positioning is particularly critical for the copy platen, copy carriage, and lens carriage servos because the calibrated corrections for them are computed with respect to their reference positions.

The initializer is considered to be the first overlay and is executed only once for each run of the EOR programs. It is overwritten in core memory by other overlays and cannot be brought into memory again. When the initializer has finished performing its functions it exits to the loader.

C.3.3 Loader

The loader's sole function is to load one of the overlays according to a code given to it upon entry. The loader always is entered from an overlay, and it always transfers control to the overlay that it has just read into memory from disk. Figure C-5 is a flowchart of the loader, and Figure C-6 pictures the flow from one overlay to the next through the loader. Before continuing on to the discussion of the remaining overlays, it is necessary to describe the operation of the CRT driver and the clock program.

C.3.4 CRT Driver

The operation of the CRT driver is critically interrelated with the functioning of the overlays. The driver's purpose is to communicate with the operator of the EOR system by way of the CRT terminal; therefore, it (1) prints outputs to the operator, and (2) reads inputs typed by

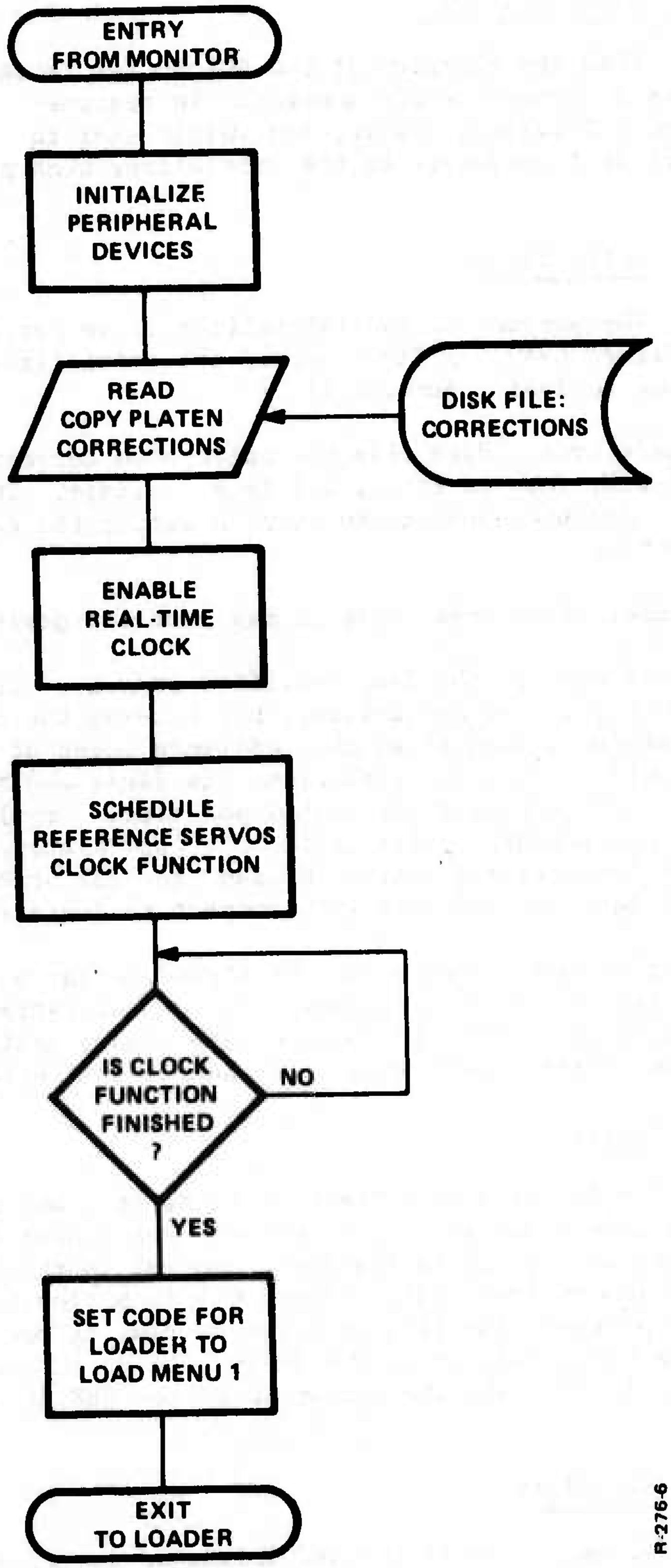

Figure C-4 - Initializer Flowchart

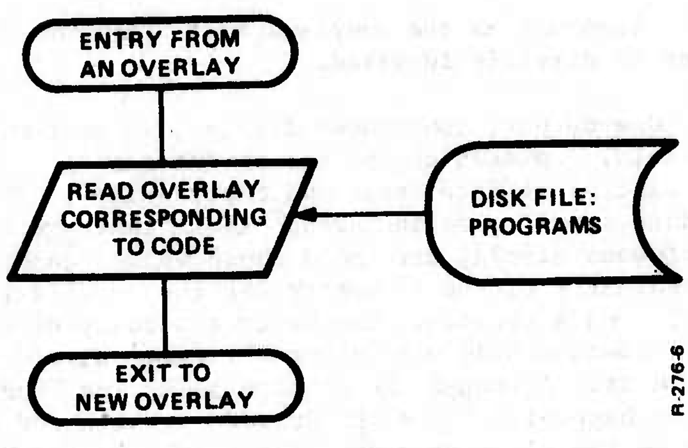

Figure C-5 - Loader Flowchart

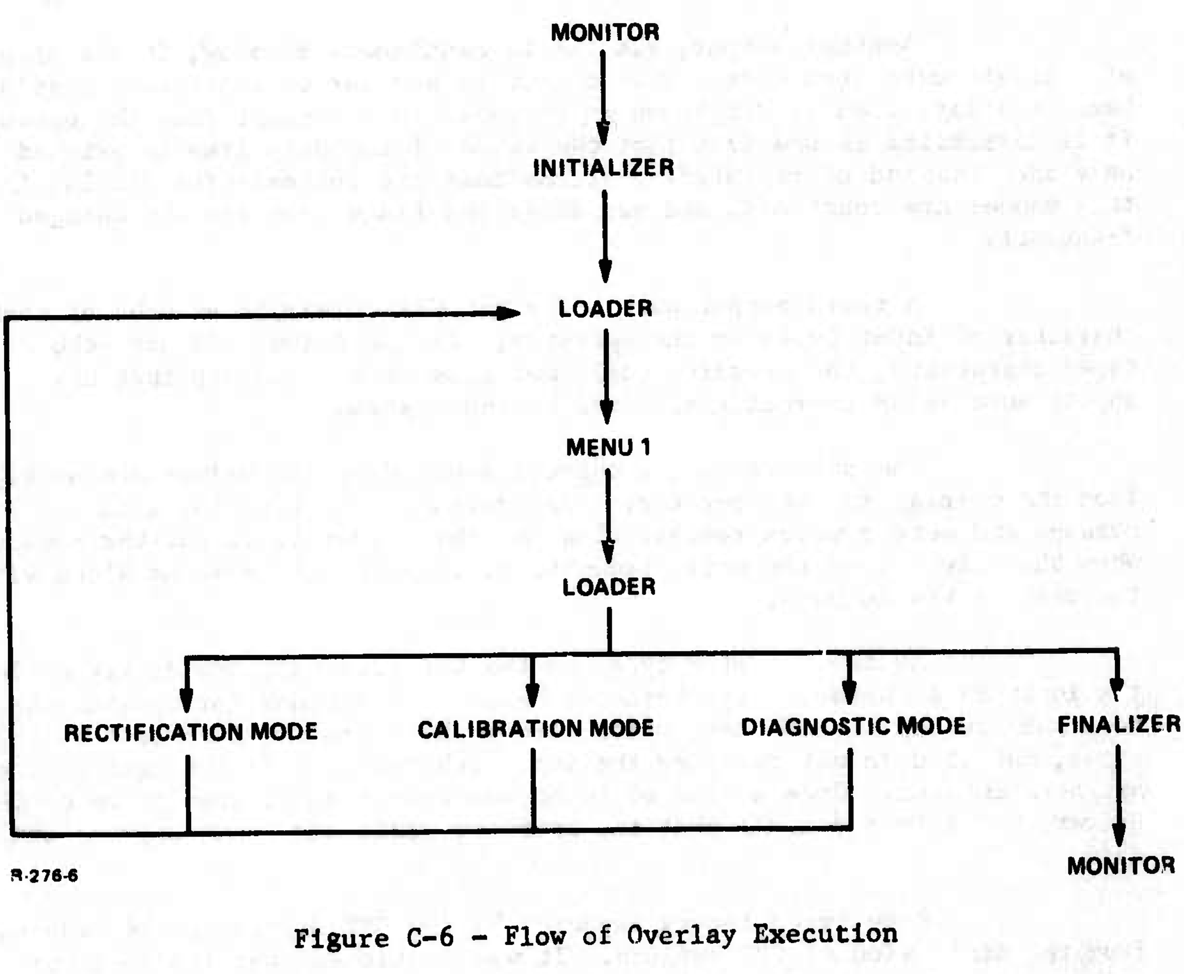

Figure C-6 - Flow of Overlay Execution

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the operator. Inasmuch as the overlays must converse with the operator, the CRT driver is directly involved.

One output, continuous display, is uniquely appropriate for CRT terminals. An area at the top of the screen is maintained for the repeated listing of data items and their values. The operator selects the data items to be included. Items that are especially suitable for continuous display are those whose values change with time; e.g., the coordinates stored in memory for the rectifier's servos. But any data item, even a constant, can be continuously displayed. Continuous display occurs concurrently with other CRT terminal I/O and in no way interferes with it. Although the display is called "continuous", it is not perpetually happening. The CRT driver performs the display only when told to do so by the clock program. The clock program keeps track of time and initiates continuous display at some fixed interval such as five times per second. Even when continuous display has been initiated, there are time lapses for handling input. Output characters are sent to the terminal one at a time and only when the terminal is ready to print them. Also, the driver is in the position to give priority to whatever must be done next. It is the CRT driver that controls CRT cursor positioning.

Another output, similar to continuous display, is the display of a single data item once. This output is similar to continuous display because a data item is displayed in response to a request from the operator. It is dissimilar in the fact that the value of the data item is printed only once instead of repeatedly. Items that are suitable for display in this manner are constants, and variables and flags that are not changed frequently.

A third output handled by the CRT driver is an echo of each character of input typed by the operator. If the driver did not echo typed characters, the operator would not know with certainty that his inputs were being correctly received by the system.

The only remaining outputs handled by the driver are messages from the overlay to the operator. The overlay fills a buffer with the message and sets a write request flag for the driver to output the message. When the driver sees the write request, it includes the message along with the rest of its outputs.

As the operator types on the CRT terminal, the driver collects the input on a character-by-character basis. It watches for special characters such as the RUB OUT key, which allows the operator to erase a typing error, but it does not decipher the input otherwise until the entire line has been entered. Once a line of input has been read to completion by the driver, the driver decides what the operator wants and takes appropriate action.

Some typed inputs expected by the CRT driver can be deduced from the discussion of CRT outputs. It was mentioned that the operator selects data items to be continuously displayed. He does so by typing in the assigned mnemonic of the desired data item followed by an action character that means "Add this to the set of continuously displayed values". The program responds by including the item in the list of those currently being displayed. The next time continuous display output occurs, the new item appears on the CRT screen.

A related input is one that requests the program to remove a data item from the list of those being continuously displayed. The operator types the mnemonic of the data item followed by an action character that says "Remove this from the set of continuously displayed values". The next time continuous display output occurs, the item no longer appears on the CRT screen.

Another CRT input concerning data items is the one that requests a value to be displayed once. The operator types the mnemonic of the desired data item followed by a question mark. The driver responds immediately by retrieving the value of the item from memory and displaying it.

The operator also has the capability of changing the stored values of data items. He simply types the mnemonic of the item followed by an equal sign and the item's new value. The driver stores the value in memory immediately. Changeable data items include program flags as well as variables and constants. An example of such a flag is the one that tells the program which one of the four servos is currently active. Incremental rate inputs are applied to the servo specified by the operator through this flag.

If the driver finds that an input typed by the operator is not one of the inputs just discussed, it defaults to the overlay currently in memory. That is, it assumes that the input belongs to and is expected by the overlay. The driver exits to the overlay so that any action required by the input can be performed.

Besides handling CRT I/O, the driver performs one other service for the overlays. It keeps track of the status of the START and STOP panel pushbuttons. The overlay sets a flag indicating that it wants to be notified when the status of the buttons change. The driver watches the buttons and exits to the overlay after a status change occurs.

Figure C-7 is a flowchart of the CRT driver. Note that it loops upon itself checking for I/O situations. Because the CRT terminal is not being used in an interrupt-driven mode the driver must be executed often to ensure that no typed input characters are missed and output of the next character in a message occurs as soon as the CRT terminal is ready. The driver's loop is interrupted only under the following conditions:

(1) A write request from the overlay has been completed.

(2) An input is not an input expected by the driver and is presumed to belong to the overlay.

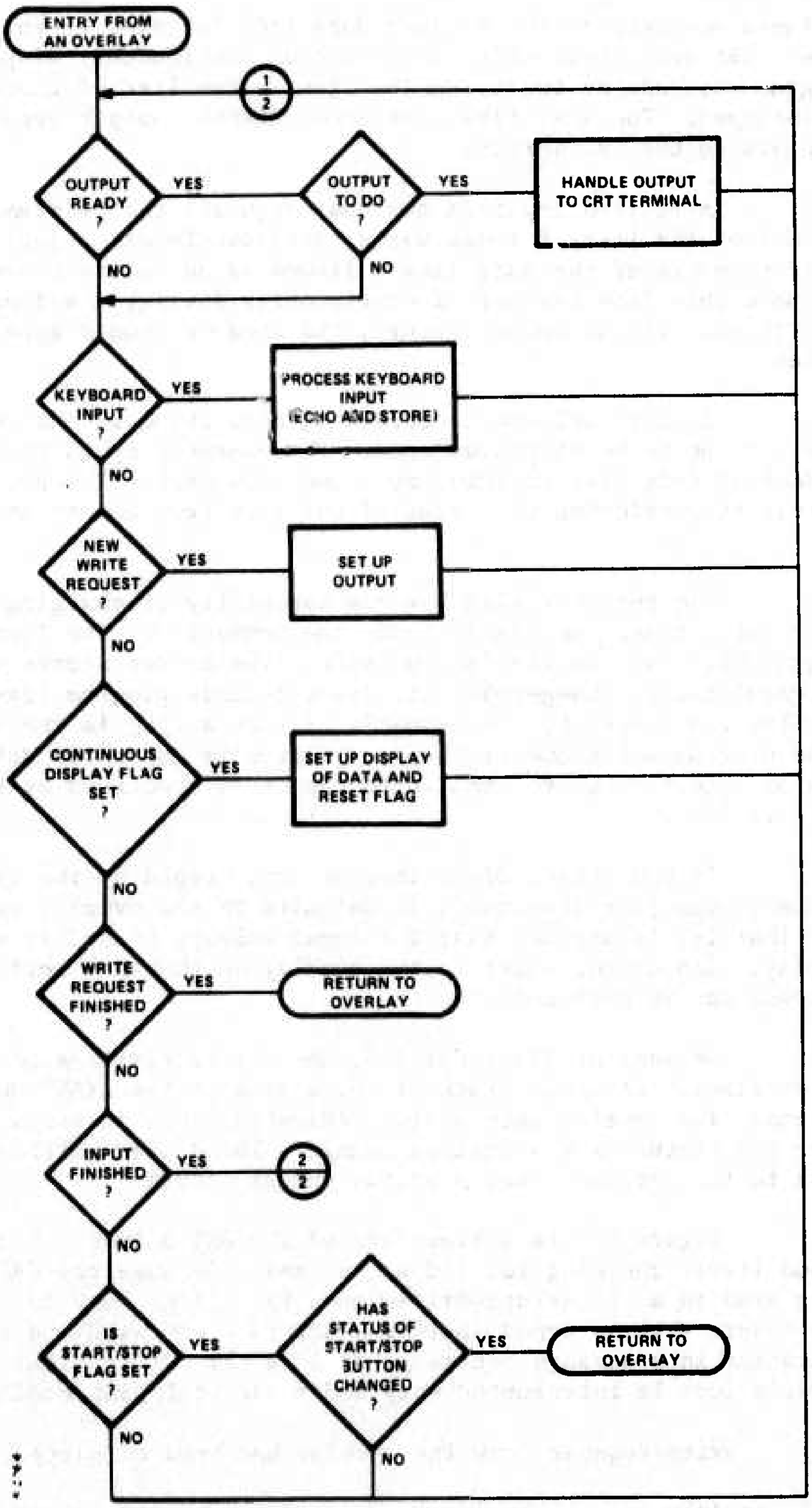


Figure C-7 - CRT Driver Flowchart (1 of 2)

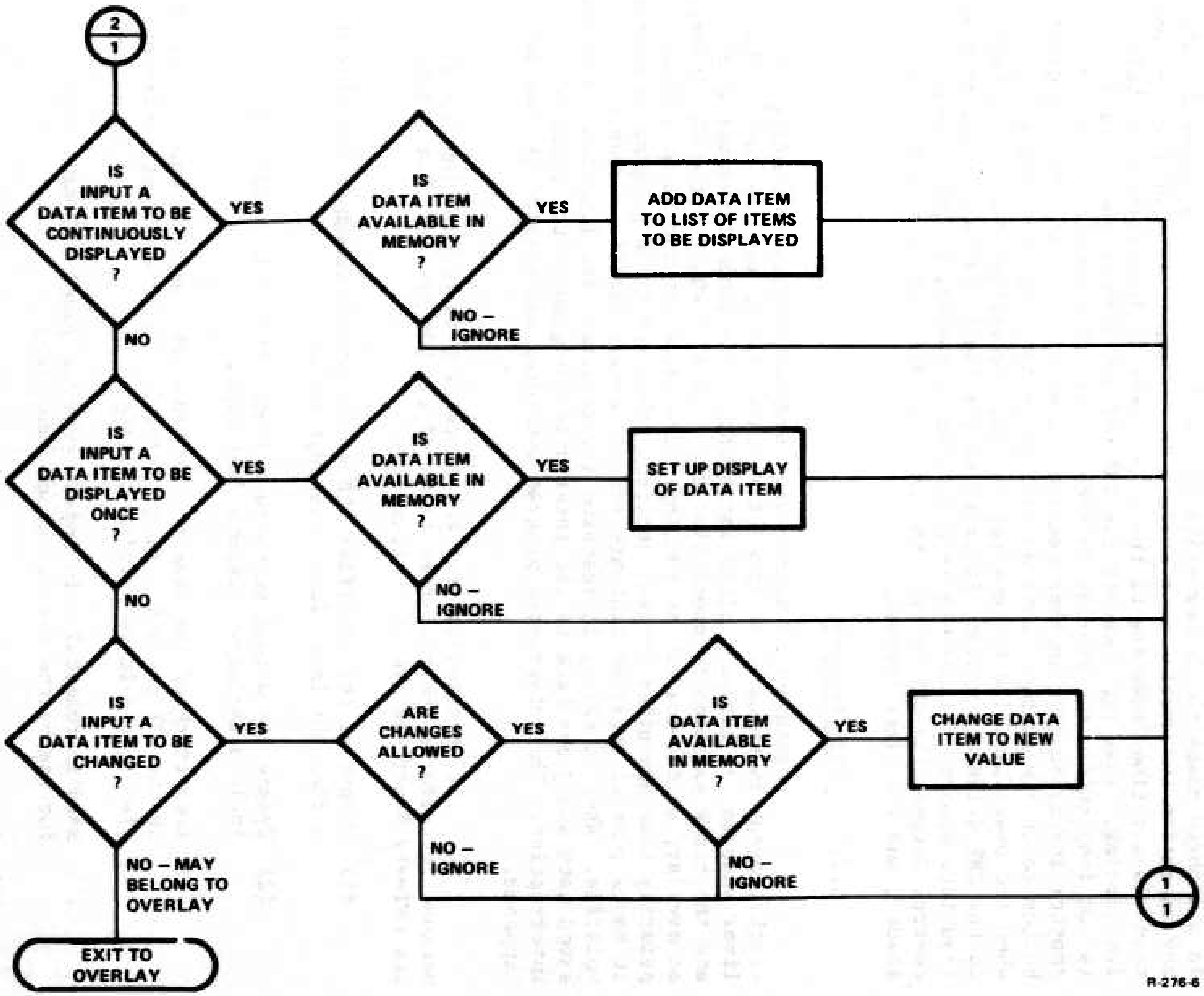


Figure C-7 - CRT Driver Flowchart (2 of 2)

(3) The status of the START or STOP button has changed and the overlay is waiting for the change.

In all three cases the driver exits to the overlay. It is assumed that any operation the overlay must perform in response to one of these situations is not time consuming to the point where it interferes with CRT functioning. That is, whenever the CRT driver exits to the overlay it is not long before the overlay returns to the CRT driver waiting for another input, sending another message, or waiting for the STOP or START button to change status. This assumption is true with one exception. When the operator tells the overlay to end, the overlay does not return to the CRT driver. Instead, it exits to the loader to have a new overlay read into memory. Figure C-8 is a diagrammed summary of the flow of control between the CRT driver, the overlay currently in memory, the loader, and the clock program.

C.3.5 Clock Program

Regardless of which other program section is running, the clock program is executed at fixed time intervals as soon as the initializer enables the hardware clock interrupts. The clock interrupt goes off and the clock executes to completion regardless of whether the CRT driver, an overlay, or the loader was running. The clock program is at a higher priority than any other program section. When the clock program is entered, it saves general register contents and any memory locations that are volatile. When it exits, it restores the registers and locations from the saved data and jumps back to the interrupted program at the point of interruption. The interrupted program continues on, unaware of what has happened.

It is essential for the clock program to have top priority because it performs the real time tasks of the EOR system. Specifically, its primary functions are as follows:

(1) Output to the rectifier the servo control commands calculated during the last clock interrupt cycle.

(2) Update the actual servo coordinates stored in memory to include the servo outputs just sent.

(3) Keep track of the time passed since the last continuous display on the CRT and set a flag to notify the driver when continuous display should be initiated again.

(4) Read incremental rate inputs from the panel and save them for use by the special clock functions.

(5) Execute the special functions scheduled by the overlay currently in memory. Such functions may include computing servo commands to be output in the next clock cycle.

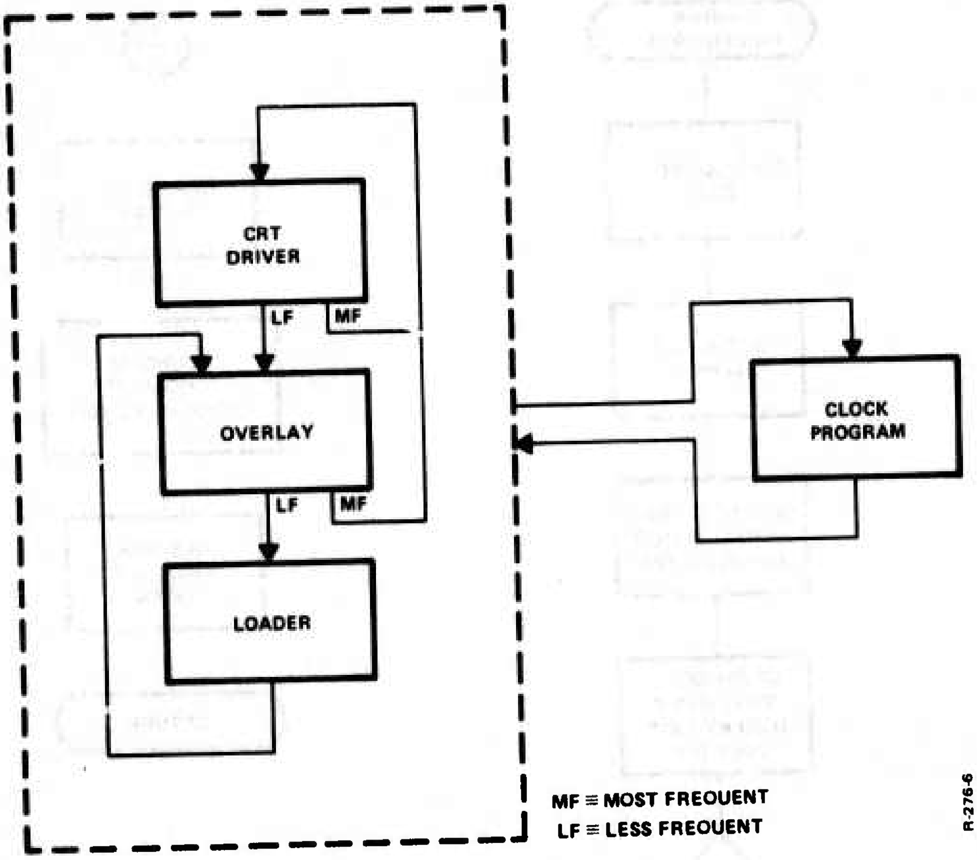


Figure C-8 - Flow of Control

Figure C-9 is a flowchart of the clock program and several special clock functions.

C.3.6 Menu 1

When the initializer exits to the loader, it gives the loader a code requesting menu 1 to be read into core. Menu 1 lists on the CRT terminal the various modes available to the operator and asks for his selection. The possible mode selections correspond directly to the four remaining overlays. The operator may choose to (1) run the rectification overlay, (2) calibrate the copy platen, copy carriage, and/or lens carriage, (3) run diagnostic routines, or (4) end the EOR programs. The operator's selection is converted to a code and menu 1 exits to the loader.

Menu 1 schedules no special functions for the clock program to call. It does, however, use the services of the CRT driver. Figure C-10, a flowchart of menu 1, does not explicitly indicate the interaction that occurs between the CRT driver and menu 1 overlay. This flowchart and the flowcharts for all of the other overlays are meant to show primarily a functional flow. Consequently, when a symbol such as the following symbol

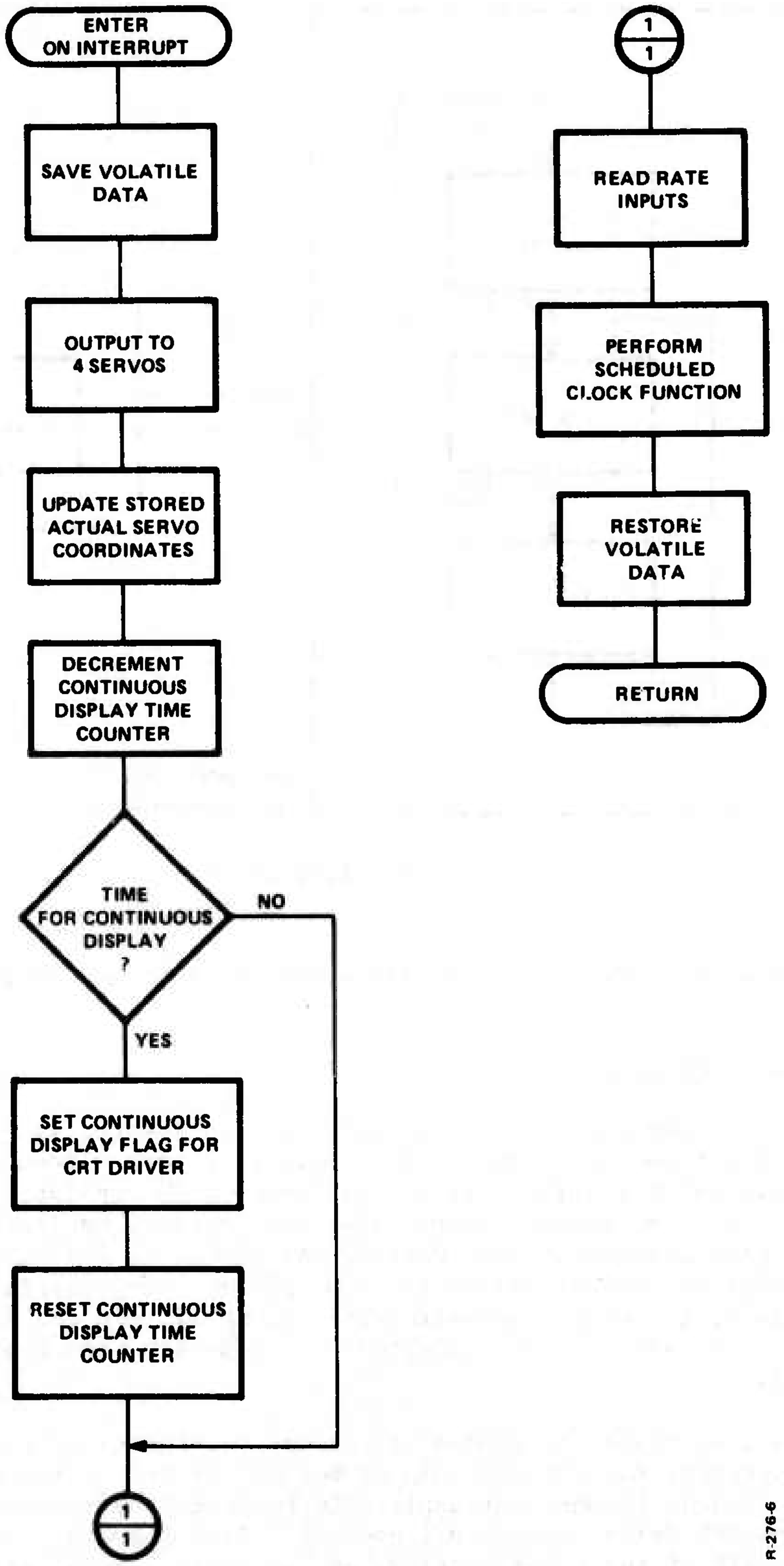


Figure C-9 - Clock Program Flowchart (1 of 4)

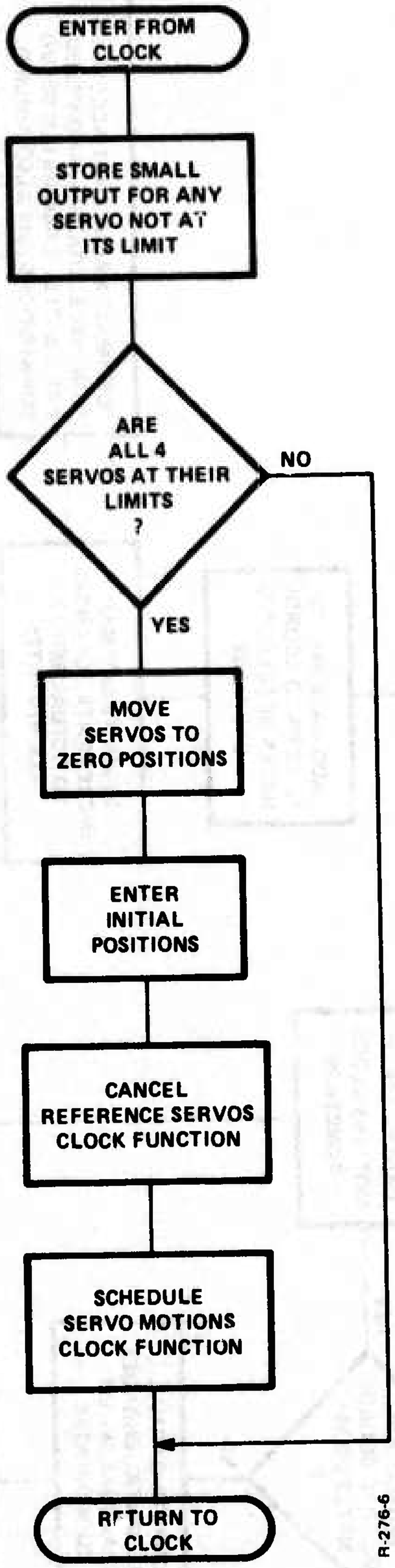


Figure C-9 - Clock Program Flowchart (2 of 4)

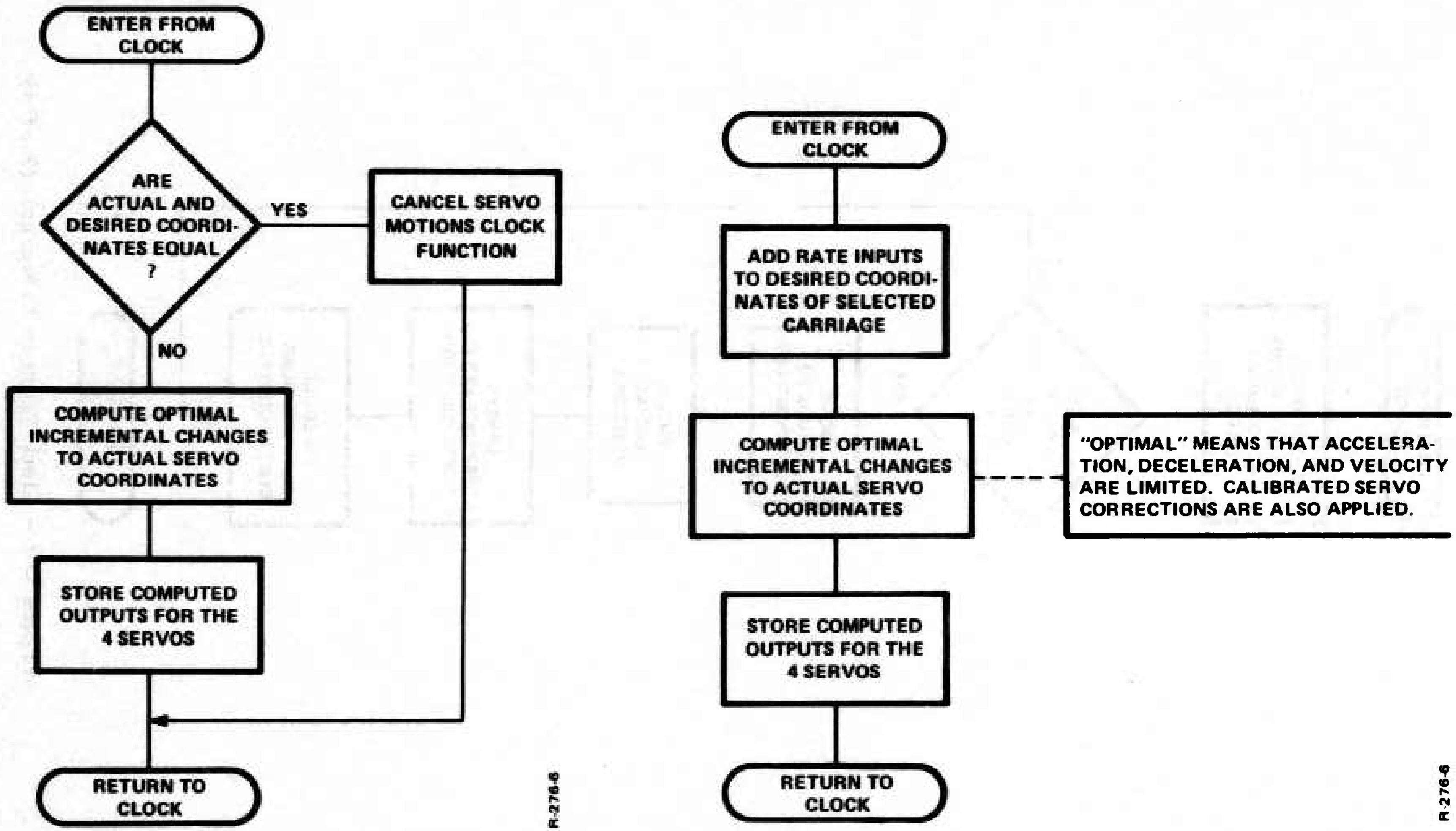


Figure C-9 - Clock Program Flowchart (3 of 4)

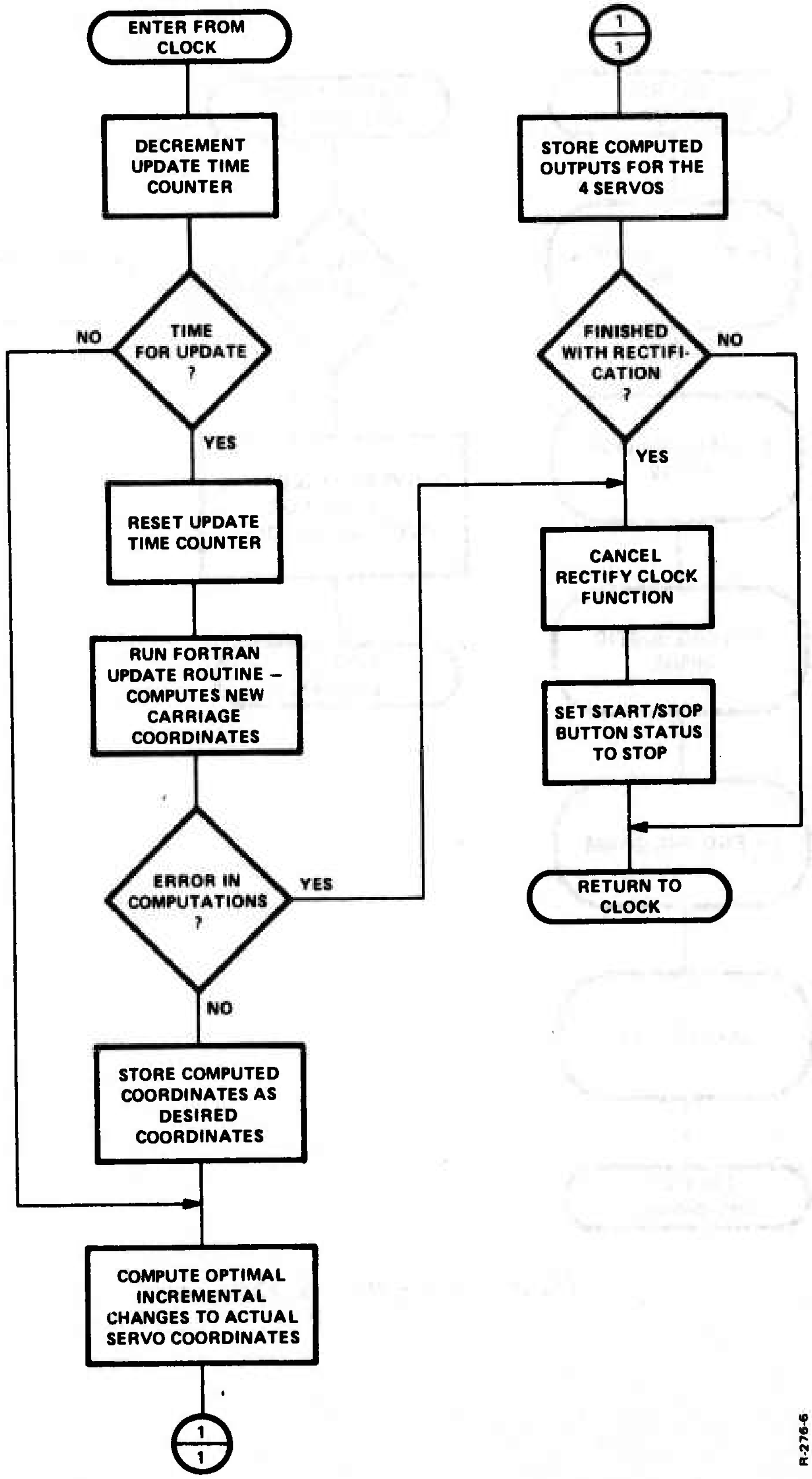


Figure C-9 – Clock Program Flowchart (4 of 4)

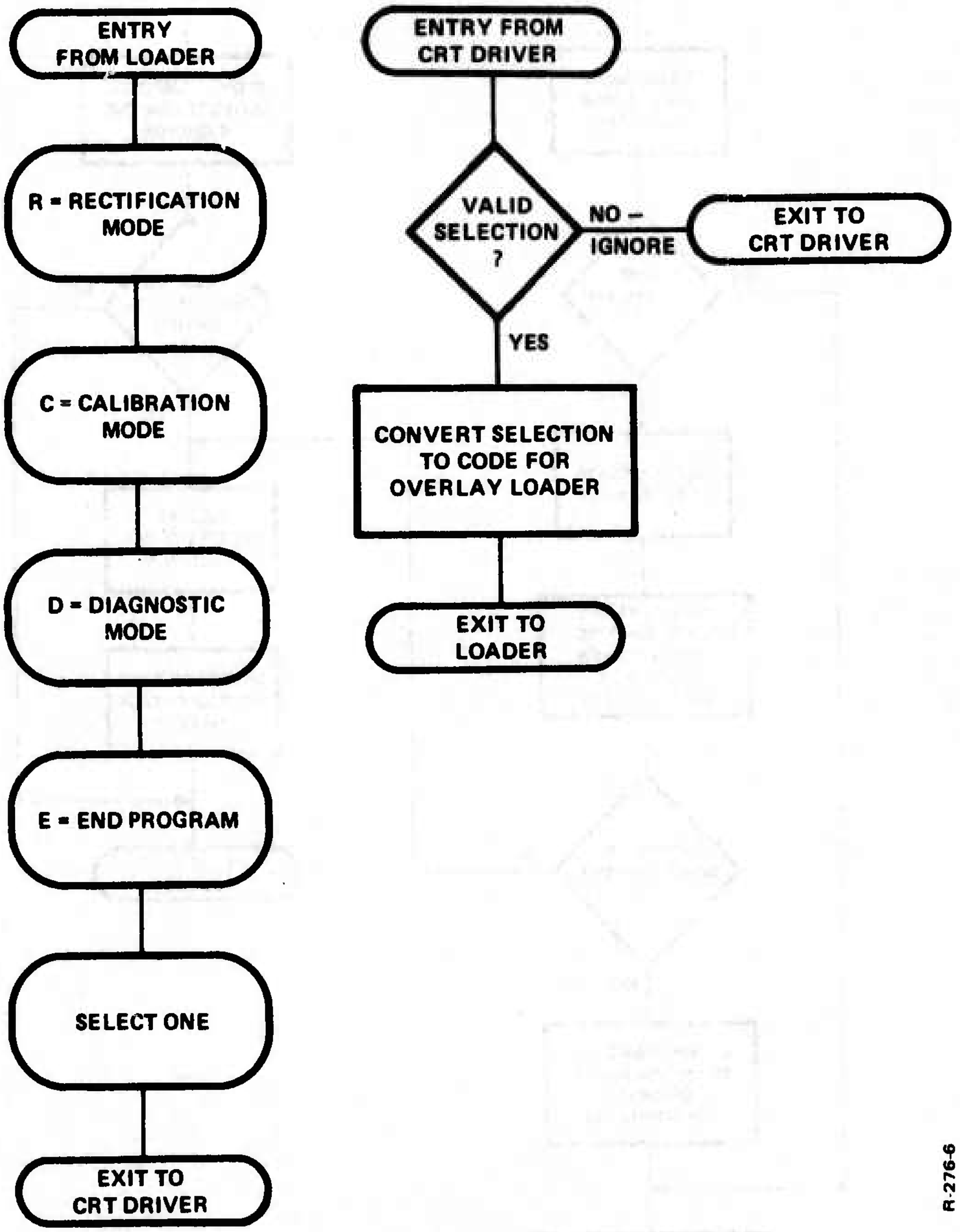
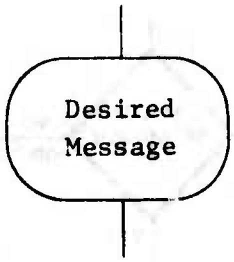


Figure C-10 - Menu 1 Flowchart

appears in the flowcharts, it implies many detailed events.



Specifically, it implies that (1) the overlay has stored the desired message in a buffer for the CRT driver, (2) the overlay has stored an address to be used as a return link when the CRT driver has finished printing the desired message, (3) the overlay has set the write request flag for the driver, (4) the overlay has exited to the beginning of the CRT driver, (5) the CRT driver has printed the desired message on the CRT screen, and (6) the CRT driver has returned to the overlay so that it can continue. Concerning inputs typed by the operator for the overlay, the overlay sets another link for the CRT driver to use when such inputs occur. The overlay may change the input link as it progresses.

C.3.7 Rectification Mode

The rectification mode (see Figure C-11) directs the production functions of the electro-optical rectifier. Obviously, it is the overlay most frequently selected during menu 1. When it is selected, the loader reads the basic rectification program and a second menu into core memory. Menu 2 then lists all available rectification options; e.g. frame, panoramic, linear enlargement, etc. Since only one option can be used at a time, the routines associated with each option are stored in a suboverlay on disk. The operator selects an option and the rectification mode overlay brings the appropriate suboverlay into memory. It also loads data items uniquely required by the selected option into memory from a special disk data file.

Each suboverlay contains at least two FORTRAN subroutines. These subroutines contain all of the mathematics for the rectification option selected. The first subroutine, called the initialize routine, functions to:

(1) Set quantities required by the second subroutine to correct beginning values.

(2) Compute initial and final magnification values.

(3) Determine the starting positions of the copy platen, lens carriage, and copy carriage.

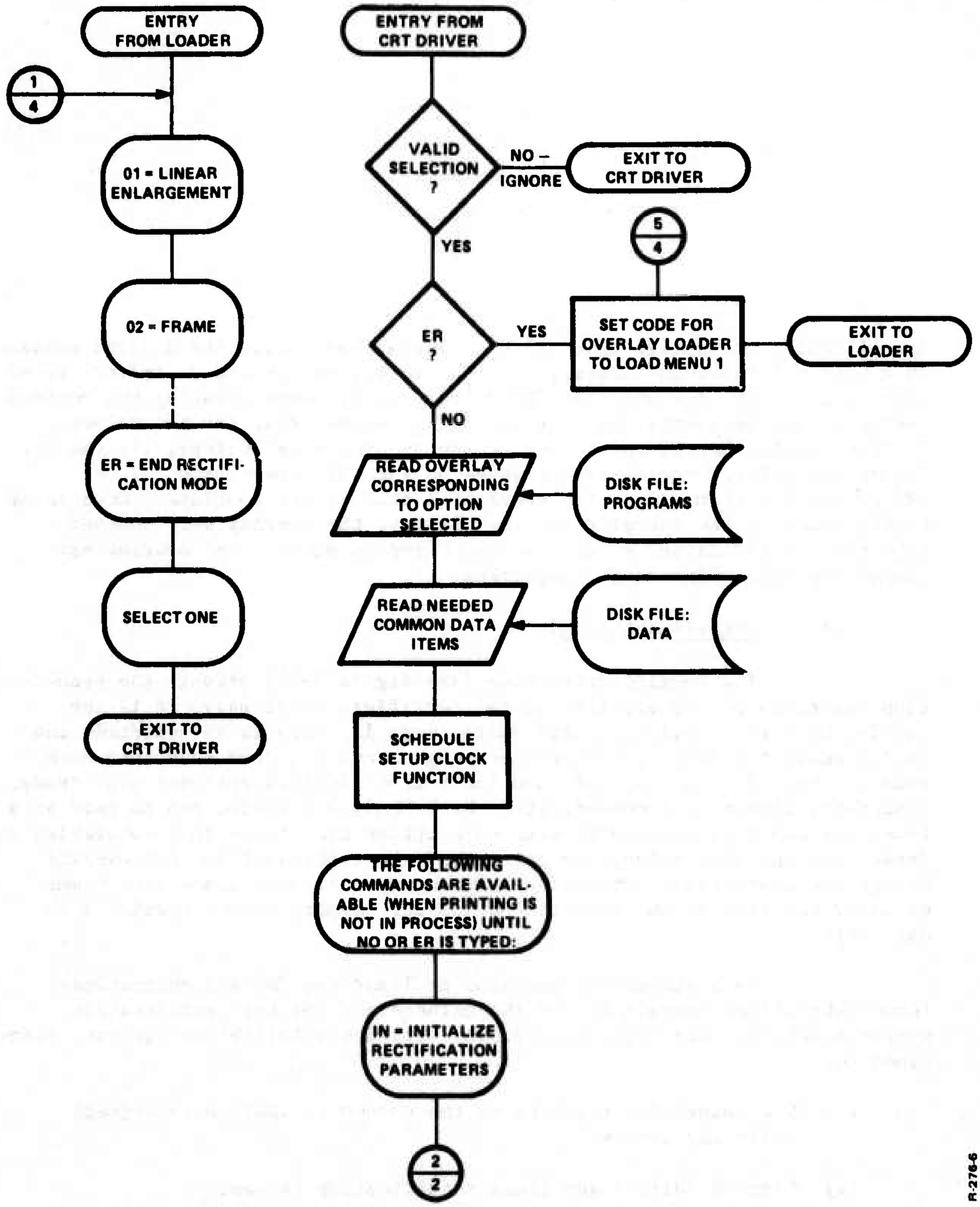


Figure C-11 - Rectification Mode Flowchart (1 of 4)

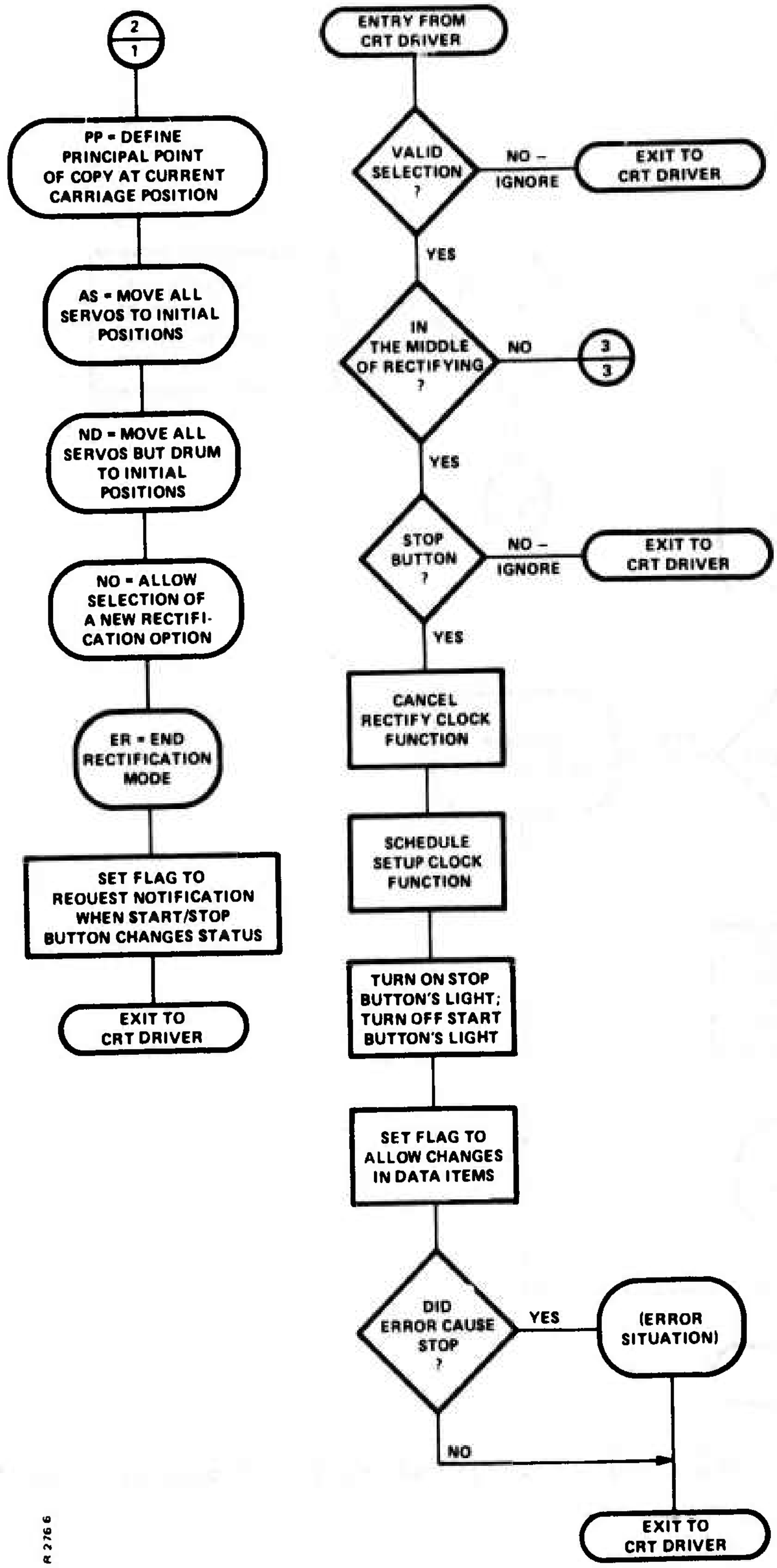


Figure C-11 - Rectification Mode Flowchart (2 of 4)

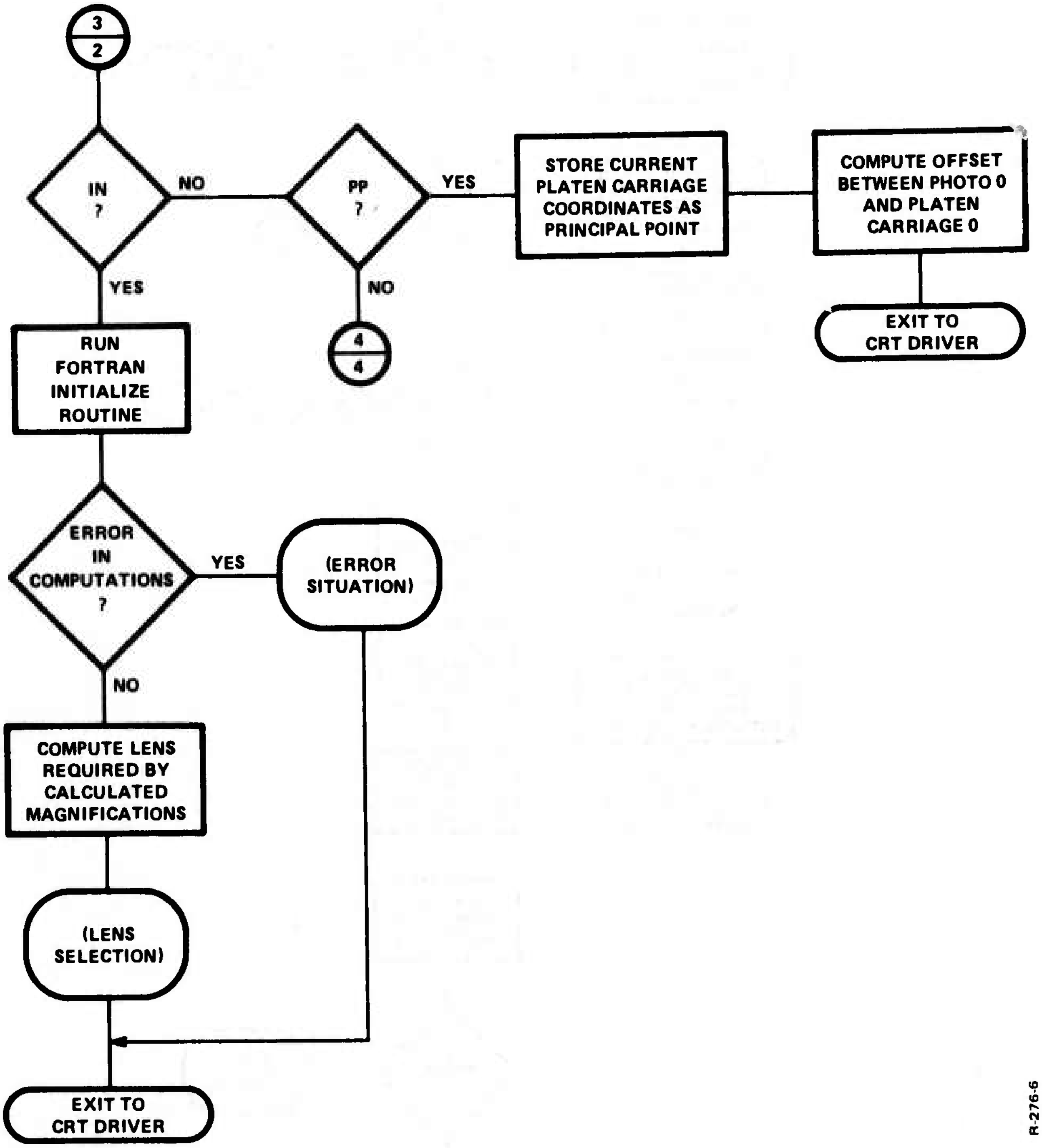


Figure C-11 - Rectification Mode Flowchart (3 of 4)

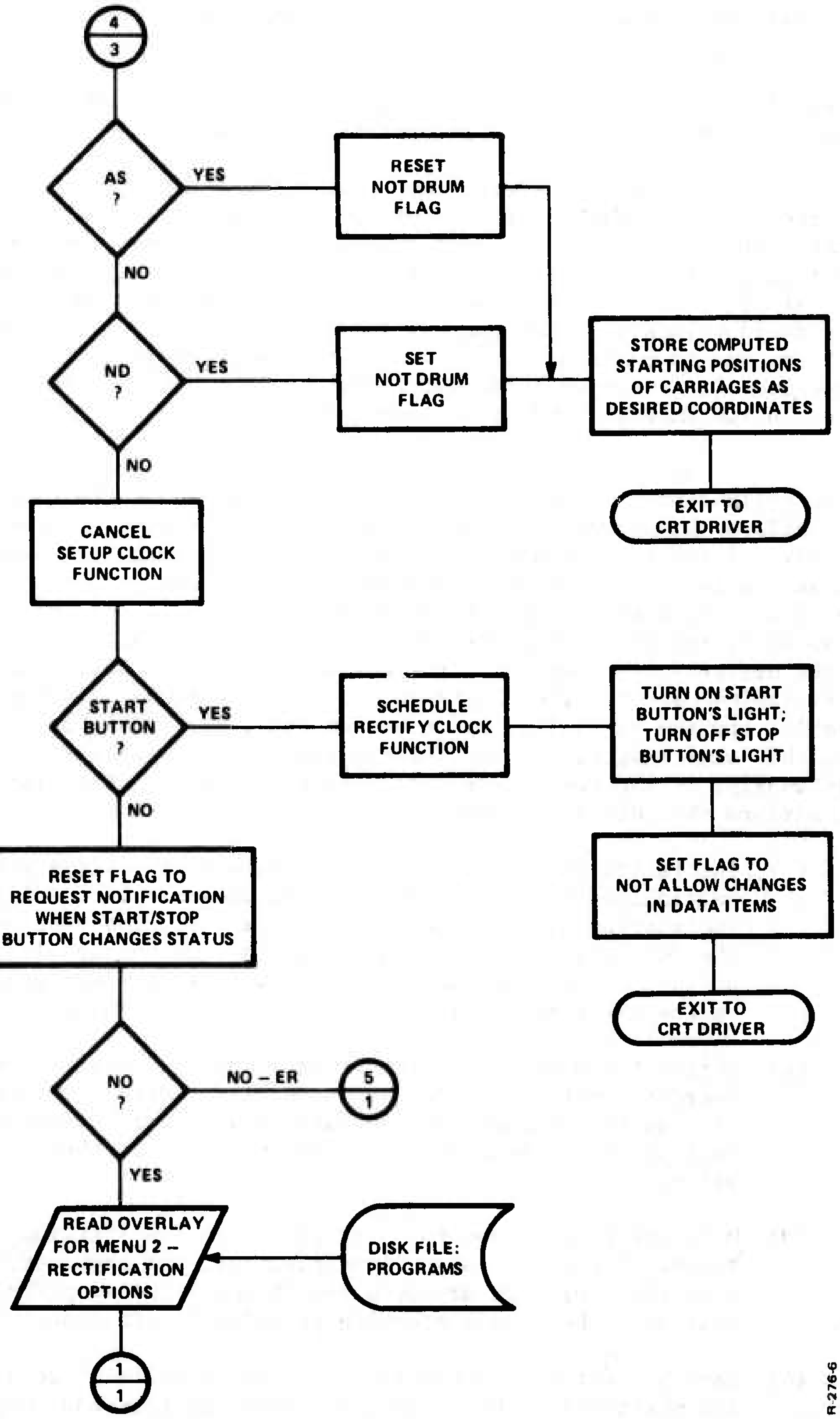


Figure C-11 - Rectification Mode Flowchart (4 of 4)

(4) Check for possible error situations and correct them when possible.

The initialize routine is not time-critical. It is called by the rectification overlay in response to an operator command.

The second subroutine, called the update routine, is executed repeatedly. It is called as part of the rectify clock function scheduled by the rectification overlay. Each pass through the routine results in positioning information for the next copy scan. That is, the copy platen, lens carriage, and copy carriage positions for the next scan are computed. The updated values are then used by the special clock function and the clock program to position the servos. The update routine obviously is time-critical. Position information must be available on time for the servos to run smoothly and at maximum speeds.

As soon as a suboverlay and its data are read into memory, the rectification overlay automatically schedules the setup clock function which allows the operator to use incremental rate inputs to move the servos manually. Setup remains active throughout the rectification overlay except when automatic rectification is actually taking place. The operator is free to load film and change the lens at any time. He also may change the values of stored data items whenever he wishes. (See Appendix C.3.4 on the CRT driver.) In fact, the operator is expected to enter the values of the variables used for the chosen rectification option. Examples of such variables are the initial position of the copy, the final position of the copy, the focal length, and the desired scale of the finished print. Additionally, at the operator's typed command, the rectification overlay will perform the following functions:

(1) Initialize the rectification parameters by calling the initialize FORTRAN routine for the chosen option. After the routine has finished its calculations, the overlay uses the computed magnification values to find the focal length of the proper lens to be used and writes the lens selection on the CRT terminal for the operator's information.

(2) Define the principal point of the copy negative by the current position of the platen carriage servo. Before issuing this command the operator must use incremental rate inputs to manually position the servo at the principal point.

(3) Move all four servos to their rectification starting positions. The copy platen, lens carriage, and copy carriage starting positions are computed in the initialize FORTRAN routine. The drum's starting position is constant.

(4) Move all servos but the drum to their rectification starting positions. This allows for printing from one copy negative and then continuing the print from another copy negative.

(5) Allow selection of a new rectification option. Menu 2 is printed on the CRT terminal once again.

(6) End rectification mode. The rectification overlay exits to the loader with a code requesting menu 1 to be read into core.

The rectification overlay actually starts rectifying in response to the START button on the operator's panel. The rectify clock function is scheduled and the setup clock function is cancelled. Changes in data items are not allowed during printing. However, it is expected that continuous display of operator-selected data items will occur throughout the printing process.

The operator can halt rectification at any time by pushing the STOP button on the operator's panel. Otherwise, the rectify clock function completes the entire print and sets the STOP button itself. Setup once again becomes active whenever rectifying has stopped.

C.3.8 Calibration Mode

The calibration mode allows the operator to measure points manually on the copy platen, copy carriage, and lens carriage for the purpose of determining servo positioning corrections. The corrections are applied to servo motions by the clock program whenever the EOR programs are operating.

The calibration mode is read into core memory by the loader whenever it is selected during menu 1. It includes data items uniquely associated with calibrating the servos. As in the case of all of the overlays, data items can be changed and continuously displayed by the operator whenever he wishes.

The calibration overlay will perform, at the operator's typed command, the following functions:

(1) Allow the operator to measure calibration points. Operator-program communication defines the servo to be calibrated. The operator then uses incremental rate inputs to locate and measure each calibration point. The operator tells the program when he is satisfied with his measurement and the program responds by storing the current coordinate of the point in memory.

(2) Store point measurements in a disk file. When the operator has finished measuring all of the calibration points for the selected servo, he has the option of storing them on disk or not storing them. By not storing measurements the operator effectively discards them.

(3) Compute corrections using the last set of stored point measurements and a set of expected point measurements. Since the set of expected point measurements never changes, it is a permanent

part of the calibration overlay. A fit between the actual and expected measurements yields the calibrated corrections for the servo. Summary results of the fit, such as the standard error and the number of points used, are printed on the CRT terminal for the operator's information.

(4) List the computed corrections on the CRT screen.

(5) Store the new calibrated corrections on disk and replace the old corrections in memory with the new set so that they will immediately be put into use.

(6) End calibration mode. The calibration overlay exits to the loader with a code requesting menu 1 to be read into core.

Figure C-12, a flowchart of the calibration mode, is not as detailed as previous flowcharts in this section. For example, measuring points calls for special clock functions and operator-program communications that are not shown.

C.3.9 Diagnostic Mode

The diagnostic mode provides a way to check the operation of some of the EOR system hardware. It is read into core memory by the loader whenever it is selected during menu 1. Figure C-13 is a flowchart of the diagnostic overlay.

As soon as it is in memory, the diagnostic mode automatically schedules the setup clock function. As in the rectification mode, the setup function allows the operator to use incremental rate inputs to move the servos manually. A flag which can be set by the operator through the CRT driver tells the program which one of the servos is to be affected by rate inputs. Consequently, the motion of all four servos can be checked independently. Setup remains active throughout the diagnostic overlay.

As in the case of all of the overlays, data items can be changed and continuously displayed by the operator whenever he wishes. Two flags in particular are expected to be changed when diagnostic mode is active. One flag, the input flag, is set by the operator when he wants to check parallel binary inputs. The other flag, the output flag, is set by the operator when he wants to check parallel binary outputs. Both flags can be set at the same time.

Once the input and output flags are set, a transfer of information occurs whenever the operator pushes the START button. In the case of inputs, the program responds to the START button by (1) reading the input registers, (2) converting the bit patterns read to a displayable series of ONEs and ZEROs, and (3) displaying the results on the CRT screen. The operator can check the operation of an external sensor such as a limit switch by applying a signal to the sensor, pushing the START button, and observing the bit pattern at the CRT terminal to see if the signal entered the computer. In the case of outputs, the START button causes the program to

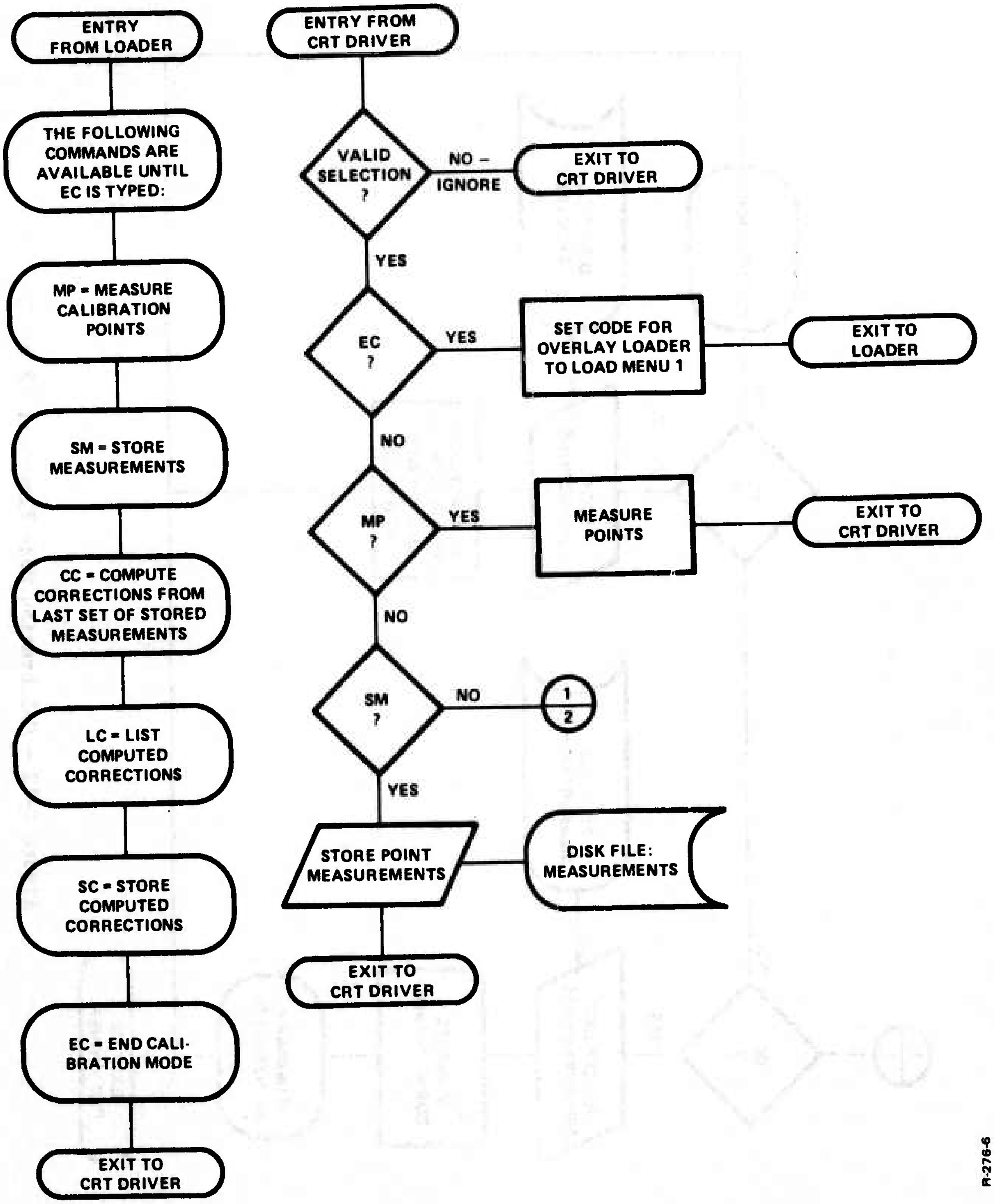


Figure C-12 - Calibration Mode Flowchart (1 of 2)

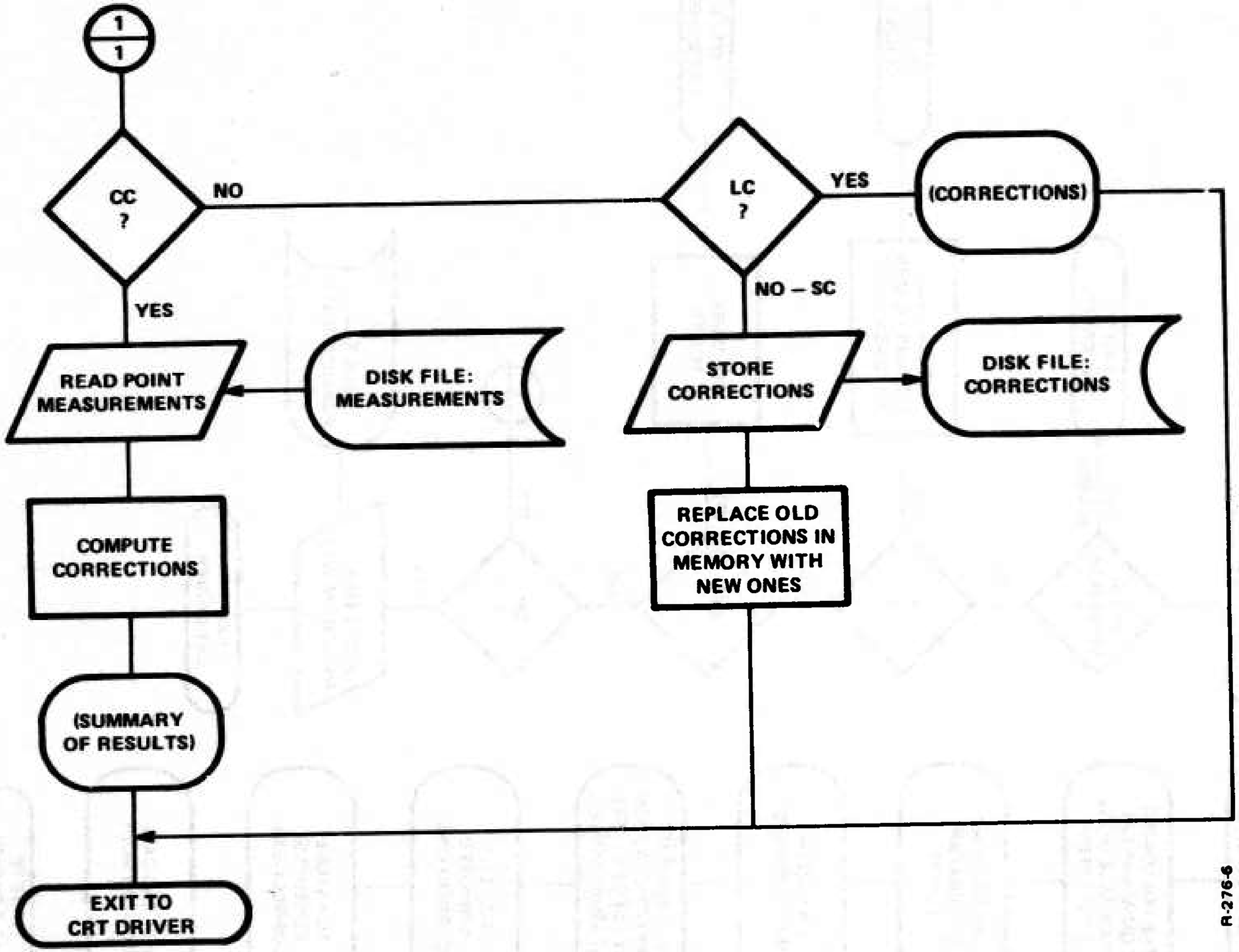


Figure C-12 - Calibration Mode Flowchart (2 of 2)

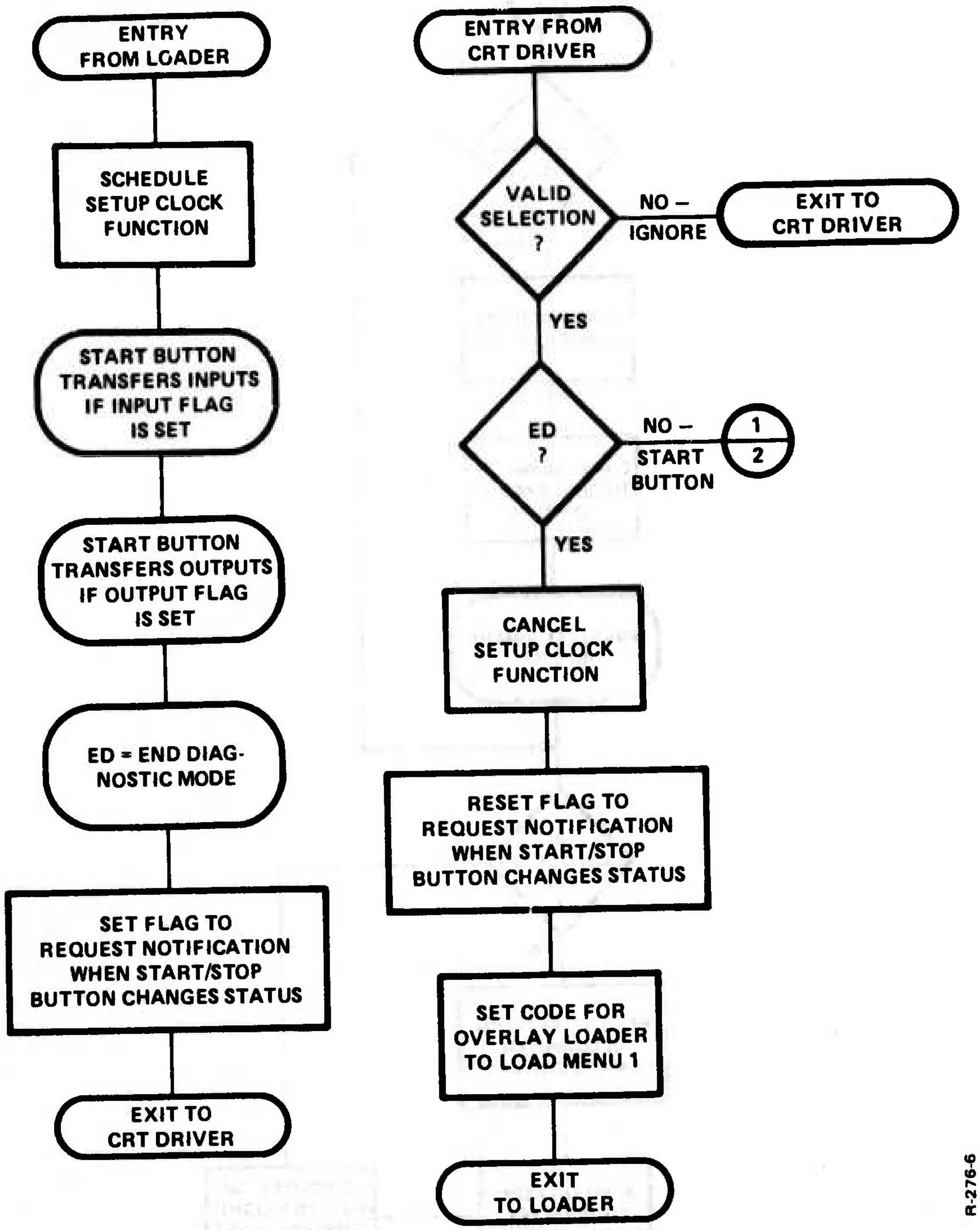


Figure C-13 - Diagnostic Mode Flowchart (1 of 2)

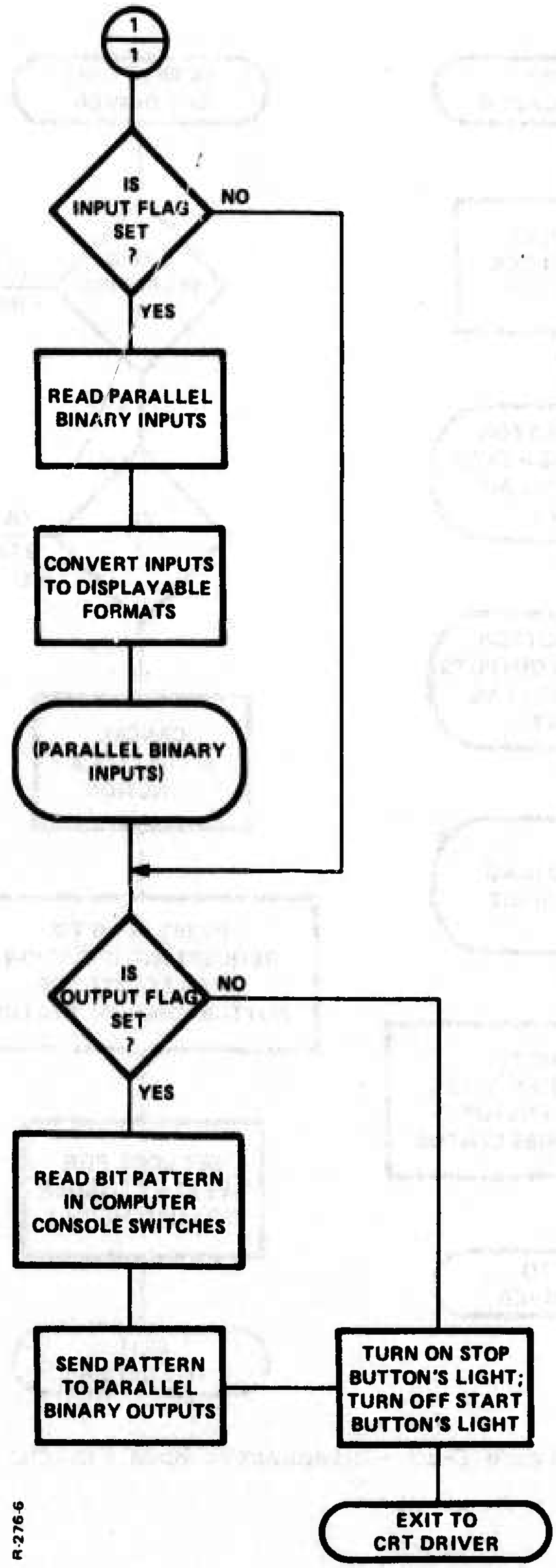


Figure C-13 - Diagnostic Mode Flowchart (2 of 2) read the bit pattern in the computer console switches and send it to the parallel binary output channels. The channels can then be checked with an oscilloscope.

The operator can end the diagnostic mode at any time by way of a typed command. The diagnostic overlay exits to the loader with a code requesting menu 1 to be read into core.

C.3.10 Finalizer

The purpose of the finalizer is to end the EOR programs. Figure C-14 is a flowchart of the finalizer. Most importantly, it returns each of the four rectifier servos to its reference position in order to save time during the next run of the EOR program. To see that time is saved, consider the fact that the initializer must find the reference positions during the next run of the programs by running into servo limits. The speed it uses is slow so that servo limit hardware is not damaged upon impact. If the servos at the end of a run are left a long distance away from their reference points, the initializer will take a long time to locate the reference positions again. At the end of a run it is a simple and short task for the finalizer to move at maximum speeds to the servo reference points. The initializer then will have a short distance to travel to the limits.

The finalizer also disables the real time clock so that the clock program will stop executing. Unlike the other overlays which always exit to the loader, the finalizer ends by exiting to the monitor.

C.4 INTERFACE

The interface unit performs the necessary switching and data transfer functions to enable the control computer to communicate with the EOR hardware. Data is transferred through the interface as 16-bit parallel digital words. As configured for the EOR, the interface has four servo output channels, two 16-bit parallel input channels, and one 16-bit parallel output channel. The servo output channels transfer 12-bit servo increments from the computer to the servo logic (4 bits are unused). The parallel input channels convey binary sensor data and rate input control data to the computer. The parallel output channel transmits binary commands from the computer to the hardware. The construction of the interface is modular, and additional channels can be easily added if future needs so require.

The actual hardware required to implement the interface depends upon the control computer selected for the system. This hardware is minimal if the DEC PDP-11/35 computer is used. If a Modcomp or Nova computer is used, special additional I/O equipment is required. The EOR interface hardware and servo logic are based on a set of printed circuit cards developed by Bendix Research Laboratories for interfacing with DEC PDP-11 series computers. The set includes a servo logic card (which is described in Appendix C.5), a parallel output card, and a parallel input card. These cards are designed to plug into a standard DEC BB-11H prewired backplane assembly (See Figure C-15).

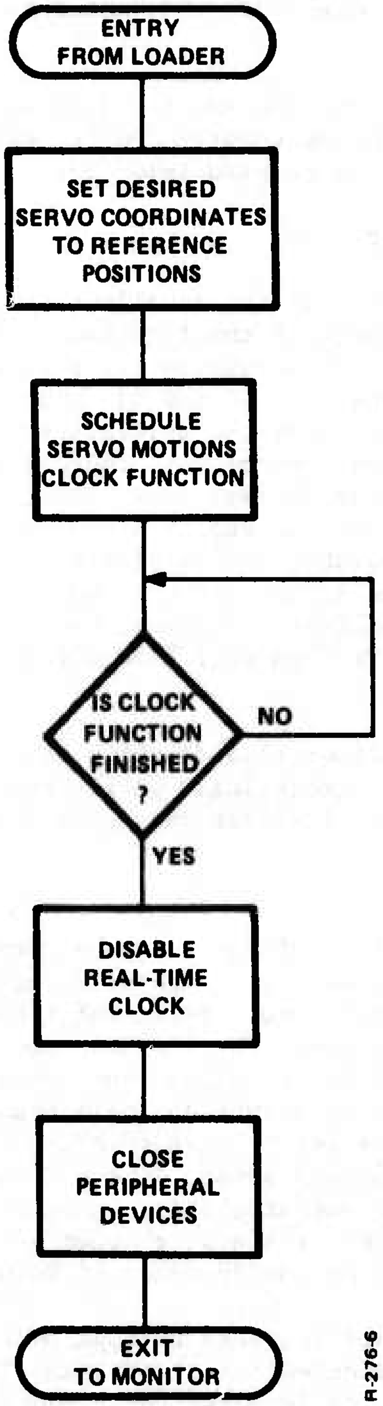


Figure C-14 - Finalizer Flowchart

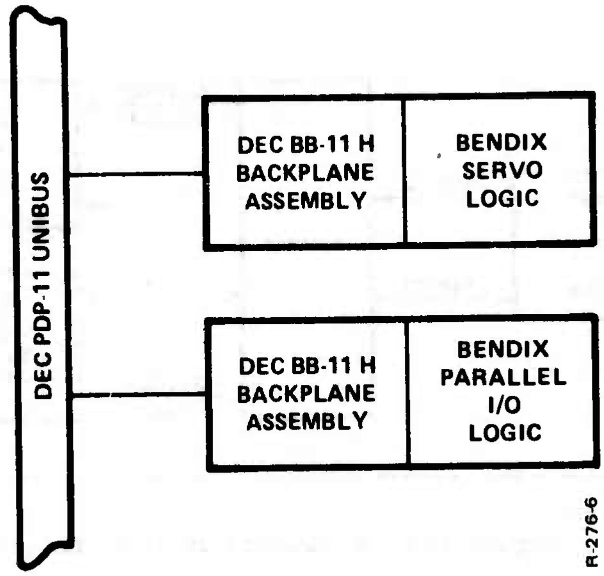


Figure C-15 - EOR Interface for DEC PDP11/35

The backplane assemblies, in turn, are connected directly to the PDP-11 Unibus. If a Modcomp or Nova computer is used, the backplane assemblies are connected through buffers to a Modcomp or Nova parallel digital I/O subsystem as shown in Figure C-16. The I/O subsystem and buffers are additional hardware required to connect the Bendix servo logic and interface cards to the Modcomp and Nova computers. Such additional equipment is not needed with the DEC computer.

Details of the four servo output interface channels are shown in Figure C-17. The servo logic cards have connectors on one end which plug into the BB-11H backplane, and connectors on the opposite end which connect to cables running to various servo components. Details of the servo logic cards are discussed subsequently in Appendix C.5. The switching and control functions of the servo interface are provided by a DEC M105 Address Selector card.

The parallel I/O interface is shown in Figure C-18. There are two parallel input cards and one parallel output card plugged into the BB-11H backplane assembly. Since the backplane assembly will accommodate four cards, one additional channel can be added without having to add another backplane. The first parallel input card primarily interfaces with the control panel. Signals from the panel switches and the rate input control are interfaced through the first card. The second parallel input card interfaces primarily with servo limit switches and quantizer zero pulse logic. The parallel input cards also have program interrupt logic which can be used for hardware interrupt functions. The parallel output card interfaces with the shutter control, a RUN status lamp, and an error alarm.

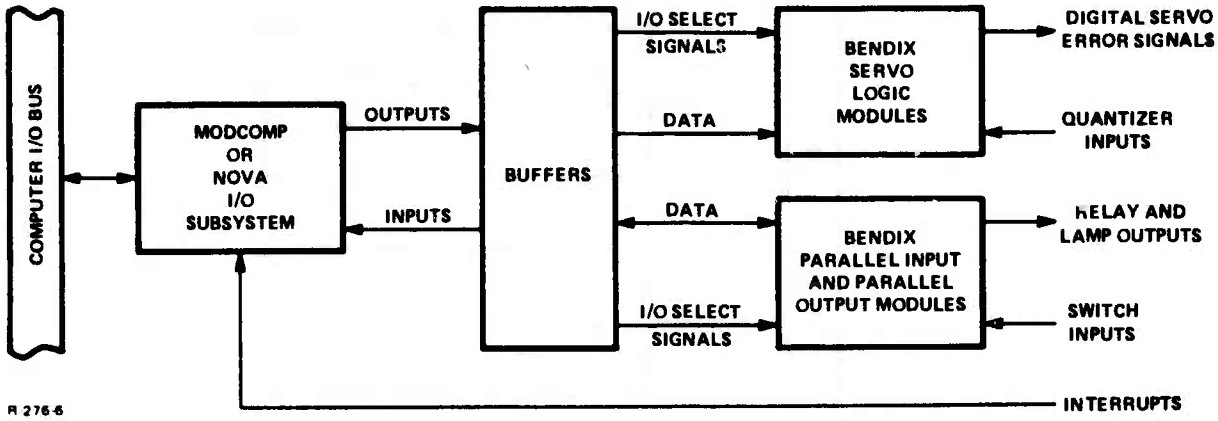


Figure C-16 - Modcomp or Nova Interface

The M105 address selector card controls the channel switching and transfer of data through the parallel I/O interface.

All of the interface hardware, including the servo logic,is housed in a separate 72 in. high cabinet. Ordinarily the servo electronics cards (D/A converter, power amplifier, etc.) are also housed in this same cabinet; however for the EOR, these cards will be installed in the EOR cabinet where the present EOR servo amplifiers are mounted. This will minimize cable noise pickup in the tachometer circuits of the various servo systems, since the cables will be shorter and isolated from digital signal wires.

C.5 SERVO SYSTEMS

Based on the servo test results and the overall objectives of the EOR improvement study, preliminary designs of improved servo systems were developed. The new design for the carriage and platen servos incorporates a modern high torque DC motor with integral tachometer to replace the present AC servo motor. The present 625:1 ratio gearbox in the copy and lens carriage drive trains is replaced with a 25:1 ratio gearbox to reduce drive train backlash. Position sensing optical encoders are used in place of the present potentiometers, and digital servo logic is used in place of the present analog servo interface circuitry. New DC servo power amplifiers are used in place of the present AC servo amplifiers.

In the improved drum drive system, a direct drive position servo is used in place of the present synchronous motor and friction drive assembly for con-

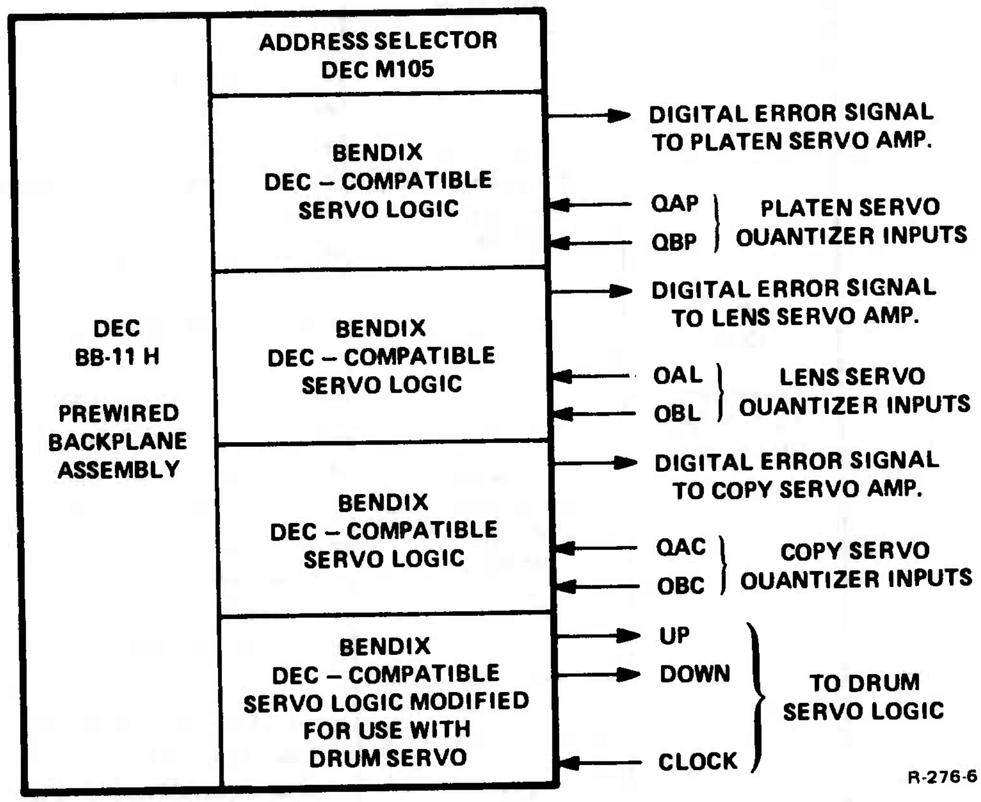


Figure C-17 - Servo Interface

trolling the print drum. This allows computer control of drum velocity and direction. The drum positioning servo utilizes a direct drive, high torque motor and precision tachometer to drive the drum. Position sensing is accomplished with an 8-inch Inductosyn in conjunction with phase-locked carrier multiplication, and digital processing circuitry to achieve 3.6 arc-second resolution.

C.5.1 Carriage and Platen Servos

The improved EOR carriage and platen servos utilize digital techniques and improved components to attain the desired improvements in performance, reliability, and maintainability. Figure C-19 shows a diagram of the improved carriage servo system. The servo hardware is essentially a digital incremental servo. The total system including computer programs, however, is an absolute positioning system. For each servo update cycle, the last commanded servo position is subtracted from the new position to determine the change required to move the servo to the new position. This function is performed by the computer programs. The change or increment is

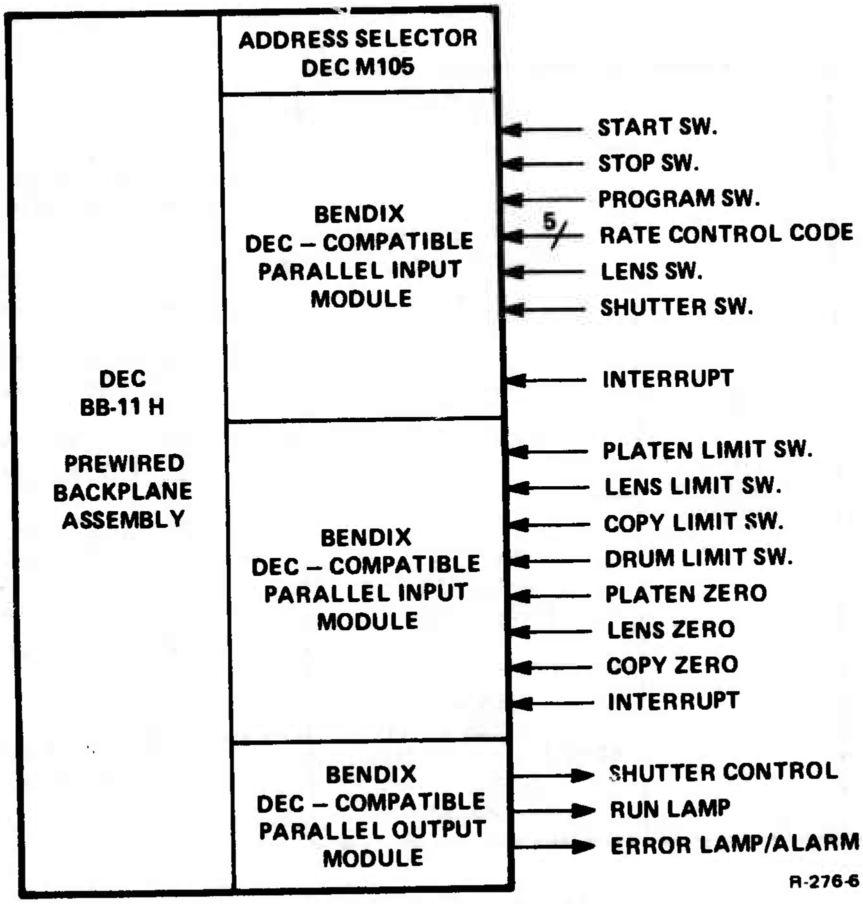


Figure C-18 - Parallel I/O Interface

transmitted from the computer to the servo hardware, which responds by moving the carriage an incremental distance in the direction and by the amount indicated by the increment. Increments are rate and acceleration limited by the computer programs. To establish the correct absolute position of the carriage when the system is started, a position initialization program drives the carriage into a limit switch. When the limit switch closure is sensed, the program backs the carriage away from the limit switch until a zero pulse is received from the quantizer. This pulse occurs once per revolution of the quantizer, and accurately indicates an initial carriage position in the vicinity of the limit switch. This initial position is a constant determined when the carriage is calibrated, and thereafter stored with the computer programs. Upon sensing that the carriage quantizer is at the zero position, the initialization program stops the carriage and enters the initial position constant as the current absolute position of the carriage for the real time control programs.

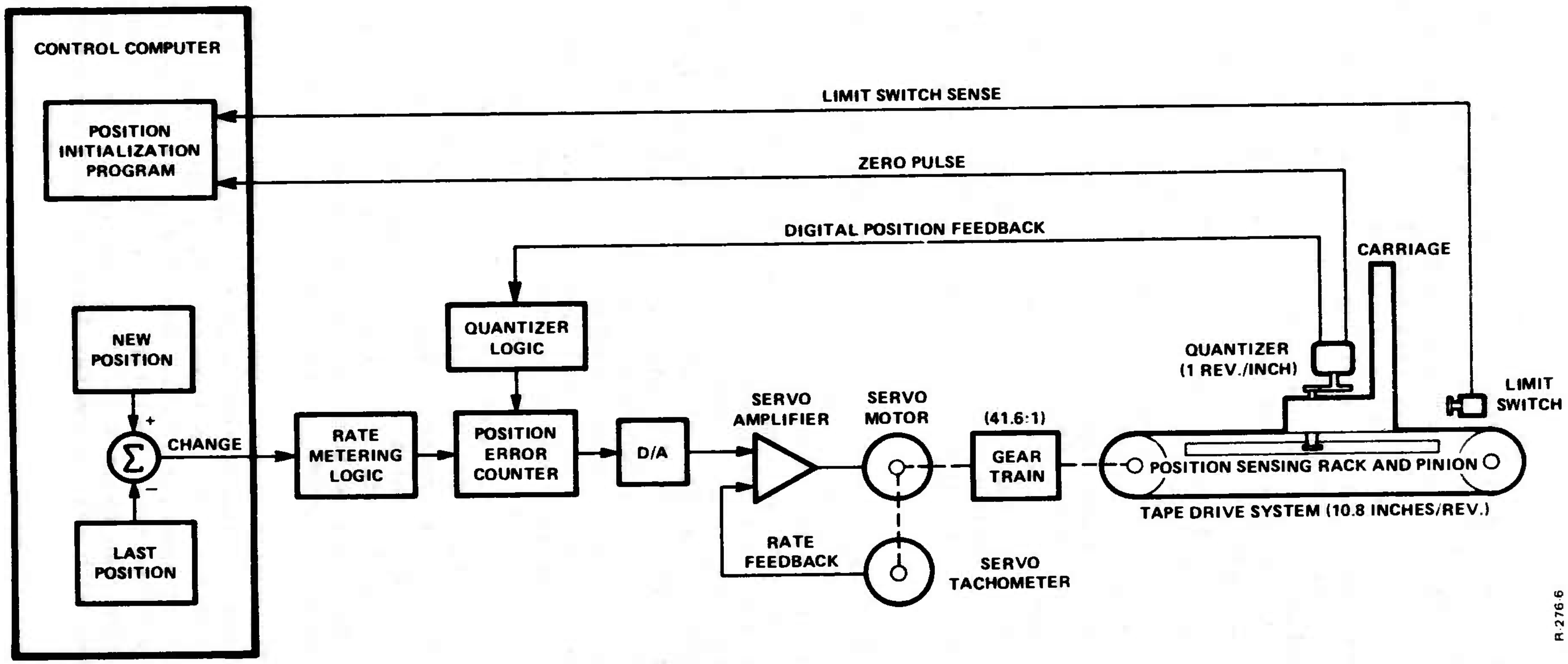


Figure C-19 – Improved EOR Carriage Position Servo

Under normal operating conditions, position changes or increments from the computer are added into a position error counter by way of some special rate metering logic. The rate metering logic causes the increment from the computer to be added to the position error counter as a series of individual pulses distributed in time over the whole servo service interval. This produces a linear interpolation smoothing of the increments from the computer, resulting in smoother servo operation. The position error signal from the position error counter is converted from digital to analog form in the D/A converter. It is then applied to the servo amplifier which in turn drives the servo motor. In the improved servo system the tachometer is directly coupled to the servo motor to eliminate backlash. The servo motor drives the carriage tape drive system through a reduction gear train. Position increments are sensed by an incremental optical encoder or quantizer mounted on the carriage and driven by the present rack-and-pinion gear system. The quantizer signals are processed by quantizer logic to determine positive and negative increments which are subtracted from the contents of the position error counter. The quantizer increments are the digital position feedback signal of the servo system. The quantizer logic produces 10,000 increments for each revolution of the quantizer. This represents 1 in. of carriage travel, so the resolution of the digital servo system is 1/10,000 in. or about 2.5 μm.

The digital circuitry including the rate metering logic, position error counter, and quantizer logic is all contained on a single servo logic circuit card. A block diagram of this logic is shown in Figure C-20. Whenever the computer transmits position increment data to the servo, the data is first loaded into the data storage register. From the storage register, it is loaded into the command counter and also applied as input to the rate multiplier. The rate multiplier then begins transmitting forward or reverse count pulses to the error counter (shown on page 2 of Figure C-20); depending upon whether the sign of the increment in the data storage register is positive or negative. The rate at which pulses are generated by the rate multiplier is proportional to the magnitude of the increment. As the error counter is counted up or down, the quantity in the command counter is counted down. This quantity is initially the magnitude of the increment. When the contents of command counter become zero, the rate multiplier is inhibited from generating additional forward or reverse pulses. This process results in the addition of the incoming increment to the error counter at a rate proportional to the increment magnitude. This has the effect of linearly interpolating between the previous value in the error counter and the new value (previous value plus increment), providing a smooth output from the error counter.

The output of the servo logic is a 12-bit two's complement digital word which is transmitted to an incremental servo printed circuit card (see Figure C-21). The incremental servo card contains the digital-to-analog (D/A) converter, a summing amplifier, a tachometer differential amplifier, and a servo power amplifier. The digital word from the servo logic card is converted to an analog voltage by the D/A converter. This voltage is summed with the tachometer feedback signal from the differential

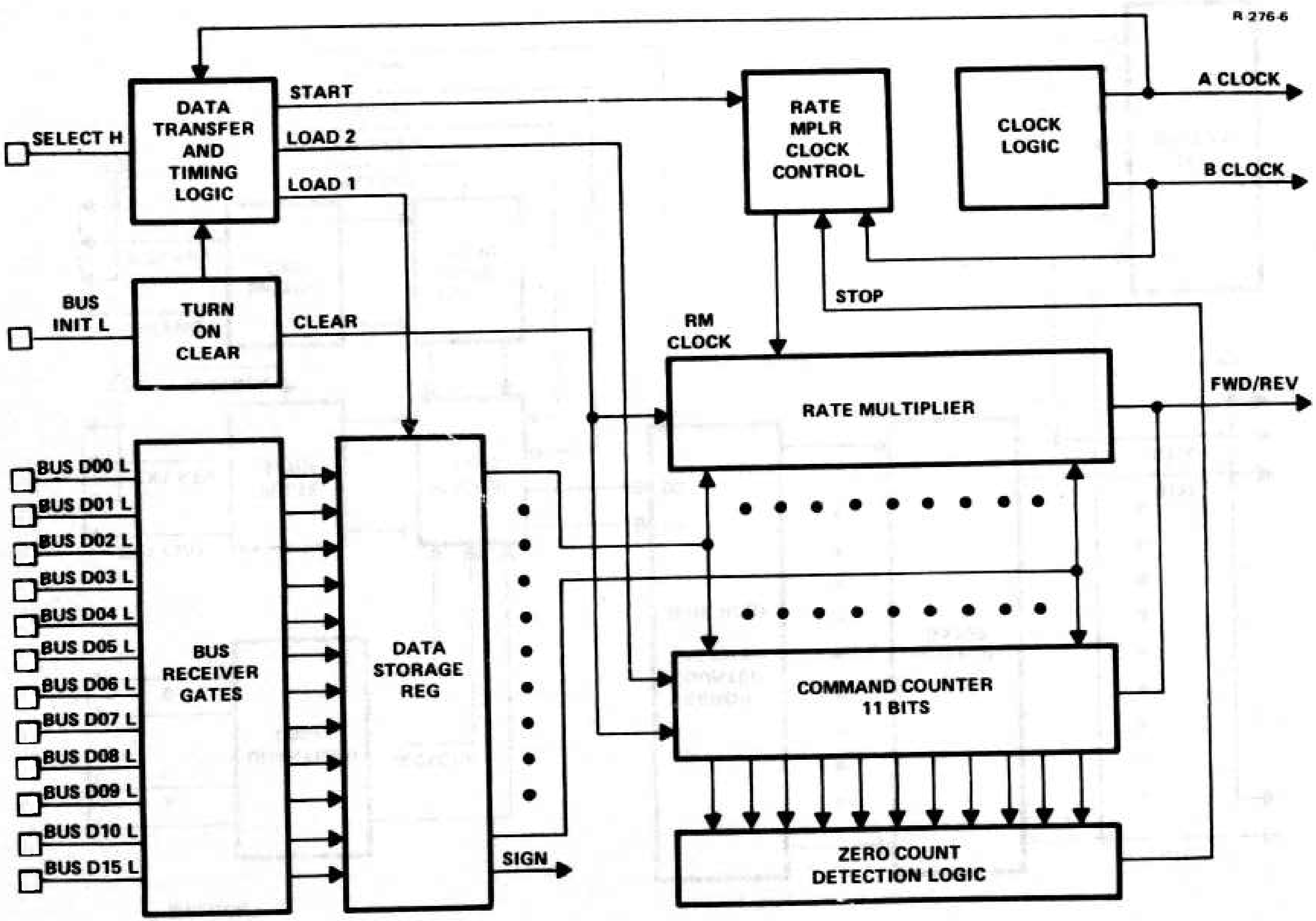


Figure C-20 - Servo Logic (1 of 2)

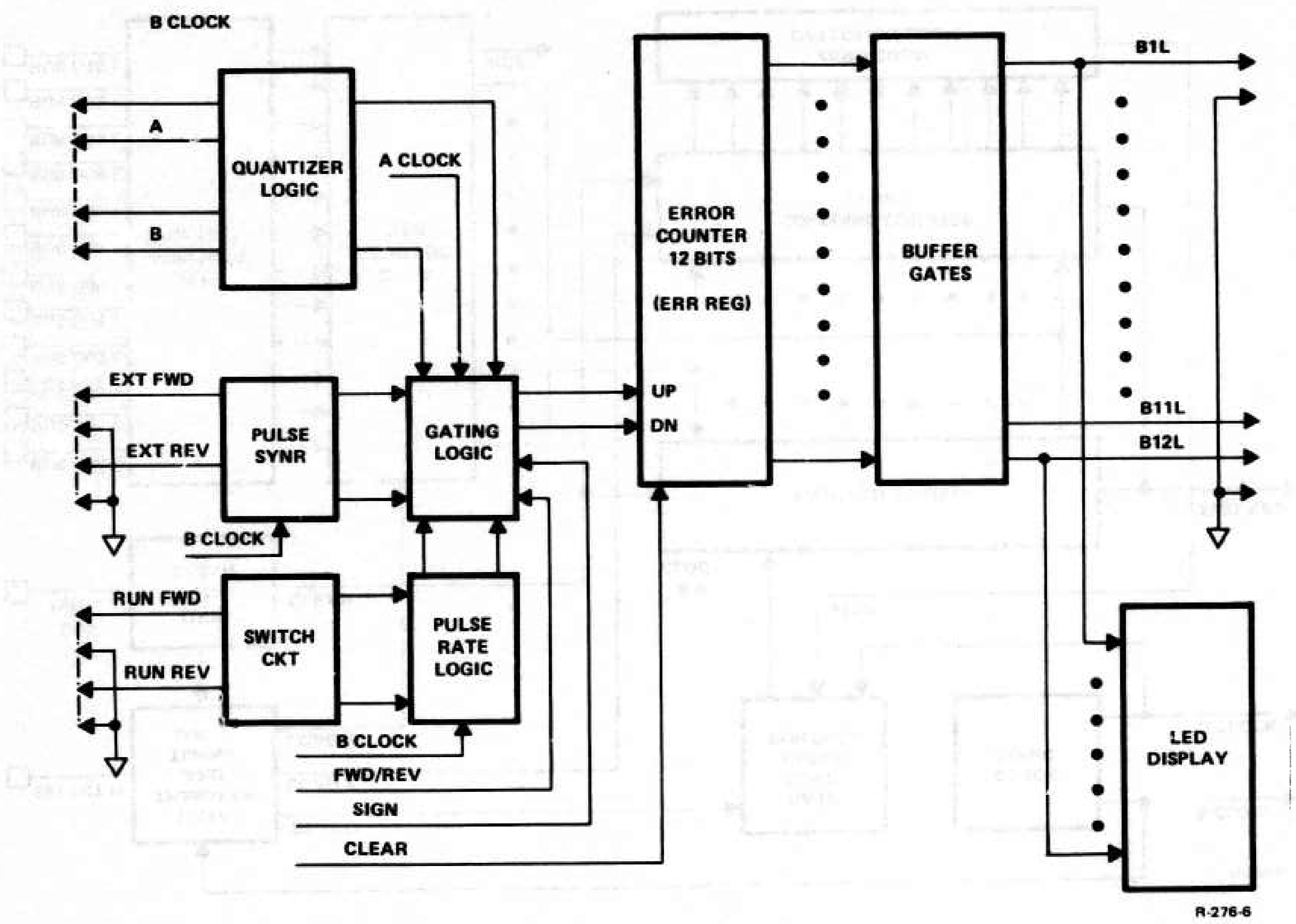


Figure C-20 - Servo Logic (2 of 2)

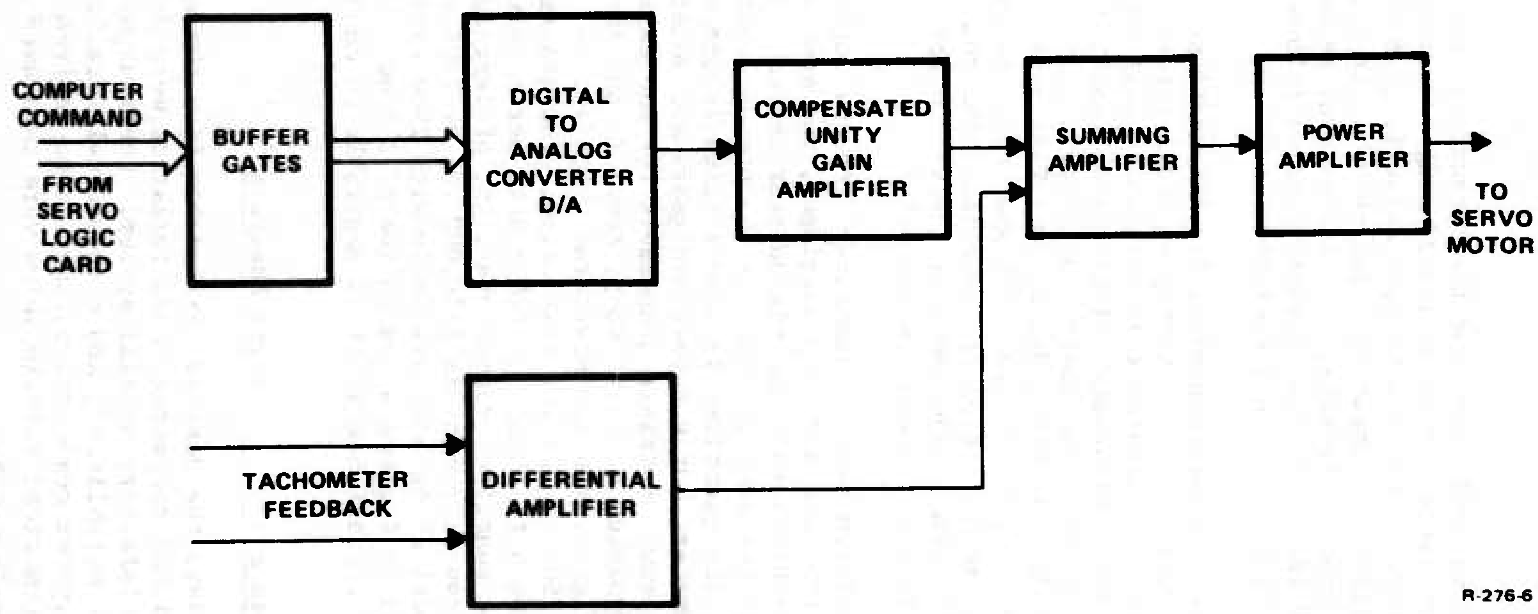


Figure C-21 - Block Diagram of Incremental Servo Card amplifier. The resulting error signal is then applied to the servo power amplifiers.

The servo logic card and the incremental servo card were developed as standard cards for servo interfacing and are used on several existing Bendix systems. They can be used directly on the EOR carriage and platen without significant alteration. The servo logic card uses standard TTL MSI and SSI integrated circuits. The incremental servo card utilizes an Analogic Corp. MP 1812A-2-D D/A converter and an Inland Controls IC-100 DC servo power amplifier as primary elements.

The servo motor-tachometer for the carriage and platen is a Torque Systems Inc. model 2212. A survey of small torque motor tachometer units resulted in the selection of this particular unit because of its low tachometer ripple ($\pm 1\%$). Tachometer ripple is an important parameter in the EOR system, which requires close control of dynamic servo errors. The new gear box is a 25:1 reduction PIC model ES-14. This gear box is in the same model series as the present 625:1 PIC gear box, and will require no additional mechanical modification for mounting. The reduced backlash of the new gear box will permit adjustment of the servos for a higher velocity constant, resulting in lower dynamic servo error.

The position sensing quantizer directly replaces the present potentiometer. For the lens and copy carriages, the quantizer is coupled to the present non-backlash rack and pinion gear system. The quantizer is physically located in the same position as the present position potentiometer. For the copy platen, the quantizer is also located in the same position as the present potentiometer, but non-backlash gears are added between the quantizer and lead screw. Suitable quantizers for the carriage and platen servos include the Dynamics Research Corp. Model 29 and the Baldwin 5V270. The quantizer itself generates two waveforms which are in electrical quadrature and have 2500 cycles per revolution. The quantizer logic multiplies by a factor of 4 to obtain 10,000 counts per revolution. Since one revolution of the quantizer represents 1 in. of carriage or platen travel, the basic servo increment is 1/10,000 in. or 2.54 μm. The Dynamics Research Model 29 is also available with 2540 cycles per revolution which when multiplied by 4 gives a resolution of 2.5 μm. This would provide some additional convenience if it is desirable to convert the system to metric units.

C.5.2 Carriage and Platen Servo Analysis

To achieve the desired performance from the new carriage and platen servos, individual component characteristics were determined which would result in a satisfactory overall system. Certain physical constraints and design goals were established, and mathematical relationships were developed to relate system component parameters to desired performance indicators. The mathematical relationships were then used to determine the requisite component parameters.

Since the new servo systems were required to operate with significantly less gear reduction, a primary consideration was the torque which the motor would be required to produce to move the carriages. Measurements of the force required to move the copy carriage established a required torque of 275 oz-in. at the tape drive pulley. A motor with the capability of producing this much torque is physically too large. With a gear reduction of about 40:1 (25:1 gearbox and 5:3 for existing pulley gearing), however, the torque requirement (with losses) is reduced to 11 oz-in., and a small torque motor can be used. A major consideration is the effect of load torque on servo error. This is determined from the servo stiffness which is given by

$$S = \frac{\text{Torque}}{\text{Displacement}} = \frac{K_T \, K_{D/A} \, A}{R_m}$$

For the selected motor, the torque constant K_T is 7 oz-in./amp, and the armature resistance R_m is 1.92 ohms. The D/A converter constant is $1.92(10)^{-3}$ V/μm. The servo amplifier gain A must be determined so that one bit of position error (2.54 μm) will overcome the maximum load torque. This requires that the stiffness S be greater than 5.32 oz-in./μm (considering an additional motor static torque of 2.5 oz-in.). The relationship for gain is then

$$A > \frac{R_m}{K_T \, D_{D/A}} (5.32) = 760$$

So a reasonable servo amplifier gain to select is A = 1000.

The velocity constant K_V of the servo system is determined primarily by the tachometer feedback gain. A model of the servo system is shown in Figure C-22(a). The inner loop is the motor-tachometer loop and represents a velocity servo system. Because of the high value of servo amplifier gain A, the system can be approximated by the diagram shown in Figure C-22(b). This is a simple first order servo system with the velocity constant equal to the forward path gain constant:

$$Kv = \frac{K_{D/A} \, K_o}{A_T \, K_G}$$

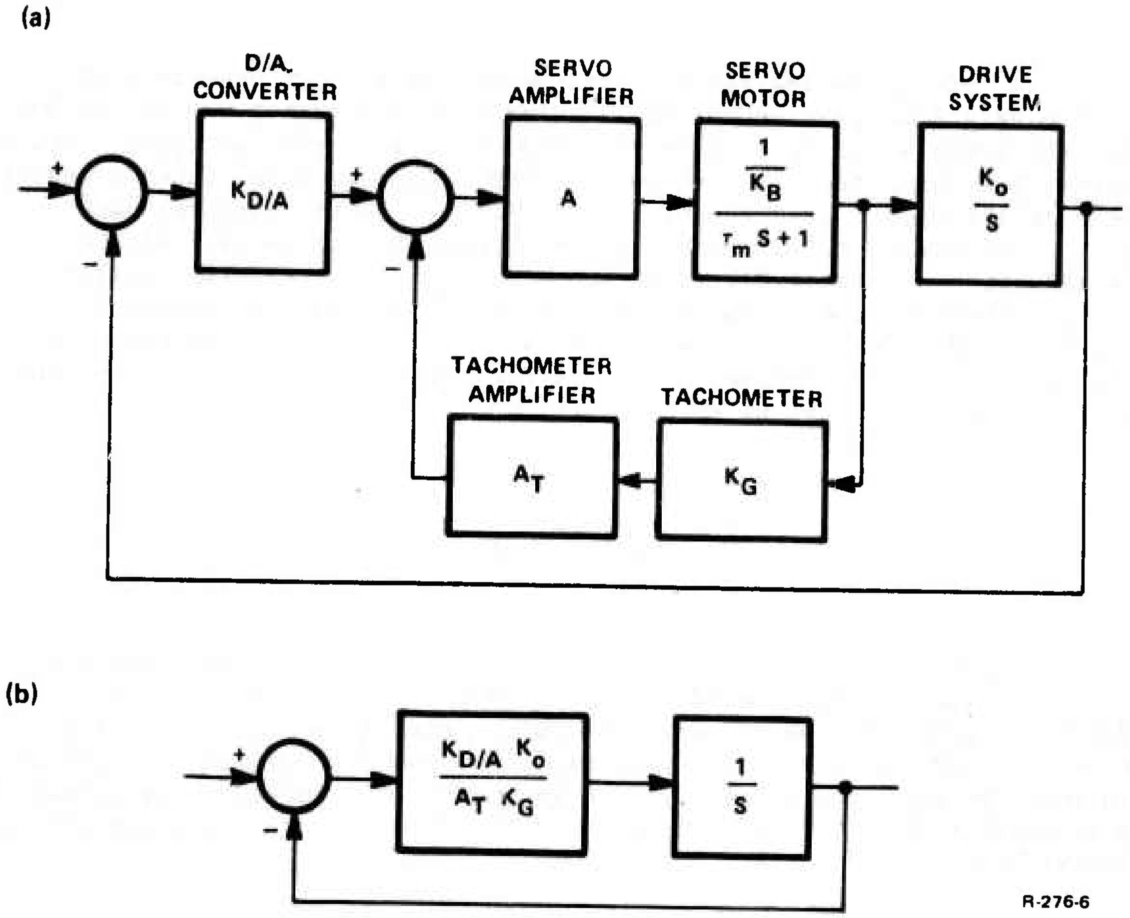


Figure C-22 - Carriage and Platen Servo Models

For the carriage servos with the tape drive and 41.6:1 gear reduction, K_o = 0.1099 mm/sec/rpm. K_G is the tachometer constant and is $3(10)^{-3}$ V/rpm for the selected tachometer. A_T is the tachometer amplifier gain to be determined. To obtain a velocity constant of Kv = 10/sec, the tachometer gain must be

$$A_T = \frac{K_{D/A} K_o}{Kv\ K_G}$$

This gives a value of A_T = 7.03 for the carriage servos. The platen servo has K_o = 0.00635 mm/sec/rpm, which gives a value of A_T = 0.406 for tachometer amplifier gain. The value is different for the platen servo because the drive mechanism is different. It is a lead screw rather than a tape drive.

The effect of tachometer linearity and ripple errors on the dynamic error of the servo is to introduce an error proportional to the tachometer output. This can be easily introduced into the analysis by a tachometer constant K_G which is in error by some percentage. This can be treated by replacing K_G with $K_G(1 + \varepsilon)$. The steady-state velocity lag error is given by

$$E = \frac{V}{Kv}$$

where V is a constant velocity. If E_1 is the velocity error for the tachometer constant $K_G(1+\varepsilon)$, then the difference $(E_1 - E)$ represents a dynamic error in the system which would be uncompensated. This uncompensated dynamic error is then given by

$$E_D = E_1 - E = \frac{V}{Kv}(1+\varepsilon) - \frac{V}{Kv} = \varepsilon \frac{V}{Kv}$$

The dynamic lag error is seen to be in error by the same percentage as the tachometer constant error. For a fixed percentage tachometer error, the uncompensated dynamic error is reduced by either increasing Kv or running at a slower velocity. At the 0.05 in./sec printing velocity presently used on the EOR, the maximum velocity of the platen is unlikely to exceed 0.1 in./sec, which is what it would be for 0.5X scan magnification. The tachometer ripple for the new servos is $\pm 1\%$, so with Kv = 10, the maximum uncompensated dynamic error would be 0.0001 in. or about 2.5 μm. The error during printing is, therefore, low enough that it will not significantly affect performance.

C.5.3 Drum Drive Servo System

The computer-controlled drum drive servo system which would replace the present EOR fixed speed drive is similar to the carriage servos in that it is an incremental servo. For the drum drive, however, the motor, tachometer, and position sensor are directly coupled to the drum shaft. The drum servo also uses an Inductosyn and its associated circuitry to generate position feedback pulses. The Inductosyn used in this system is capable of an accuracy of about 2 arc-seconds; corresponding to about 1.4 μm travel at the edge of the print drum. High accuracy Inductosyns were originally developed for the U. S. Air Force for use in theodolites and missile guidance equipment. They have also been used extensively in the numerical control machine tool industry. The drum positioning servo system recommended here for the EOR has been used very successfully on the Replacement of Photographic Imagery Equipment (RPIE) which was developed for the Defense Mapping Agency.

A diagram of the drum servo system is shown in Figure C-23. The servo system is essentially ar incremental type servo. The computer programs subtract the last drum position from the new position to determine a change or increment which is transmitted to the servo nardware. An absolute drum position is maintained within the computer, but it doesn't necessarily correspond to the absolute position of the drum. Since the drum position is not compensated, there is no need for exact position determination. The drum position is initialized by driving the drum into the limit switch and backing out some fixed distance.

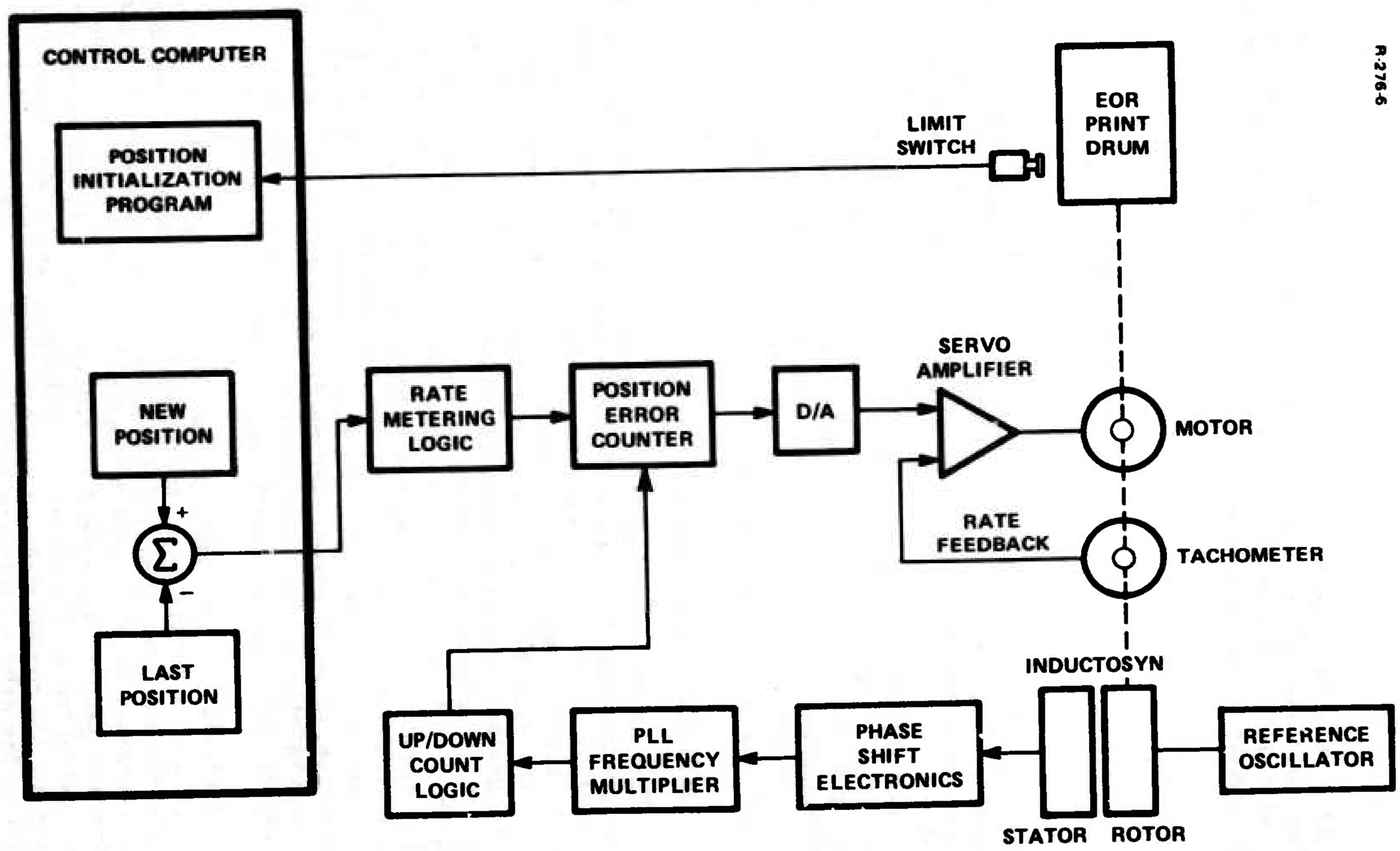


Figure C-23 - EOR Drum Position Servo System

Increments from the computer are metered out to the position error counter over the servo output service interval. The rate at which individual pulses are added to the position error counter is proportional to the magnitude of the increment. In this manner, the rate metering logic performs a linear interpolation between the last value in the error counter and the new value. This interpolation is important for achieving smooth servo operation. Position feedback pulses are received by the position error counter from the Inductosyn electronics. The contents of the position error counter are converted from a digital value to an analog voltage by the D/A converter. This analog signal is then applied to the servo amplifier which in turn drives the servo motor. Rate feedback stabilization of the servo is provided by a tachometer connected to a summing input of the servo amplifier.

The drum servo rate metering logic, position error counter, D/A converter, servo amplifier, motor, and tachometer are functionally the same as the corresponding components in the carriage servo system described earlier. The rate metering logic is, in fact, identical for the drum and carriage servos. The Inductosyn and its associated electronics, however, are much more complicated than the quantizers and quantizer logic of the carriage servos.

A diagram of the Inductosyn position sensing system is shown in Figure C-24. The primary component of this system is the 720-pole, 8-inch Inductosyn. The rotor of the Inductosyn is excited through slip rings by a 10 kHz sinewave reference oscillator. The two outputs of the stator are sinewaves whose amplitudes are proportional to the sine and cosine respectively of a rotation angle. The output signal amplitudes complete one cycle for each degree of shaft rotation. The Inductosyn, therefore, produces 360 cycles per revolution. The variable amplitude sinewaves are applied to a phase shift network which converts the signals to two sinewaves which are constant in amplitude, but shift phase with respect to one another as the Inductosyn shaft turns.

The constant amplitude sinewaves are applied to limiters which produce square waves, retaining only the zero crossing (phase) information. The 10 kHz square waves are then multiplied by a factor of 125 in frequency and phase by the phase-locked loop (PLL) frequency multipliers. The 1.25 MHz signals emerging from the PLL multipliers are 125 times more sensitive in phase shift to Inductosyn shaft angle motion than the 10 kHz input signals. The 1.25 MHz signals are phase-detected to produce quadrature sinewaves of zero carrier frequency, similar to those produced by an incremental optical encoder or quantizer. That is, the waveforms change in value as the Inductosyn shaft turns and are DC values when the shaft is stationary. The phase detector output signals are shaped into square waves and used to generate pulses from the resulting zero-crossing transitions. This is done in the 8X pulse generator which produces the final Up/Down count pulses from the zero-crossing transitions. The Up/Down count pulses are then applied as position feedback pulses to the position error counter (Figure C-23).

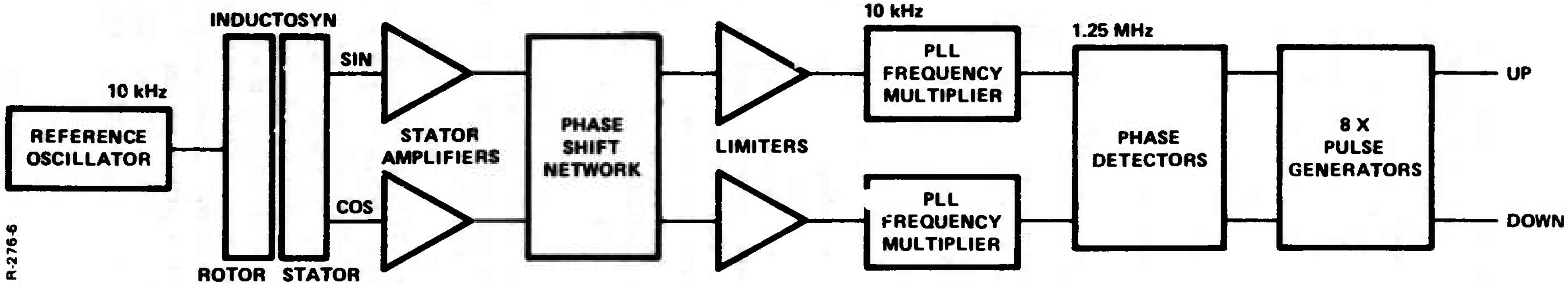


Figure C-24 - Inductosyn Position Sensing System

The PLL multiplication and 8X logic effectively increase resolution of the system to produce 360,000 pulses per revolution of the Inductosyn. The resolution of the system is, therefore, 0.001 deg, corresponding to about 0.0001 in. or about 2.5 μm of film travel on the drum.

The particular Inductosyn used in the recommended system is an 8-inch model EL-918 unit manufactured by AA Gauge Division of U. S. Industries, Inc. It has 720 poles and is accurate to within 1 to 2 arc-seconds (dependent on mounting scheme). The torque motor for the drum drive is a Magnetic Technology Model 6980-195-030. The motor has a torque sensitivity of 331 oz-in./amp and can develop 10 ft-lb peak torque. The tachometer is a Magnetic Technology model 7200-160 special performance tachometer with ± 0.1% ripple. The drum drive electronics which were developed by Aerotech Inc. for Bendix Research Laboratories as part of the RPIE program are available for use in the EOR system without further development work. The Inductosyn manufacturer AA Gauge also uses this type of servo system in their machine tool drive systems. Alternate vendors are therefore available for electronic components of the drum drive.

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